ORDER

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

6560.21A

12/4/89

SUBJ: SITING GUIDELINES FOR LOW LEVEL WINDSHEAR ALERT SYSTEM (LLWAS) REMOTE FACILITIES

1. PURPOSE. This order transmits siting guidelines for locating sites and determining pole heights for Low Level Windshear Alert System (LLWAS) remote anemometer stations (appendixes 1-3).

2. DISTRIBUTION. This order is distributed to branch level in the Program Engineering Service and to division level in the System Maintenance Service in Washington headquarters; to branch level in the regional Airway Facilities divisions (except AAL and AEU); to branch level in the FAA Depot and Facility Support Division at the Mike Monroney Aeronautical Center; and to Director level at the FAA Technical Center.

3. CANCELLATION. Order 6560.21, Siting Guidelines for Low Level Wind Shear Alert System (LLWAS) Remote Facilities, dated 2/19/88, is canceled.

4. BACKGROUND. The LLWAS is designed to detect the existence of horizontal windshear conditions on an airport and around its perimeter and to alert controllers when these conditions are hazardous. The system consists of an array of remote anemometers and the base station processing and display equipment (located in the air traffic control tower building). Communication between the remote sites and the base station will be via radio links unless landlines are readily available.

5. SITING GUIDELINES. Proper siting is essential for an effective LLWAS, but often complex to implement. The LLWAS project office has initiated several different approaches to assist in proper siting of sensors.

a. Appendix 1 presents general considerations for siting LLWAS. To further assist regions, a joint team of LLWAS engineers from FAA headquarters and the FAA Technical Center are available to resolve problems resulting from site-unique situations.

b. Appendix 2 gives detailed guidelines for the design of the anemometer array on and around the airport. In addition, the Flight Information Systems Branch, ACN-230, will prepare an initial layout of proposed sensor locations at each airport based on maps, aerial photos, site surveys, and knowledge of idealized arrays for microburst detection.

Distribution: A-W(PS)-3; A-W(SM)-2; A-X(AF)-3(minus AAL/AEU); A-Y(FA/DE)-3; A-Z-1

Initiated By: APS-340

c. Appendix 3 provides detailed guidelines for mitigating the effects of obstacles and terrain on the siting of individual anemometers. To facilitate application of these guidelines, the FAA Technical Center has provided technicians with floppy disc, PC-based program for determining correct heights and distances away from obstacles.

6. APPLICABILITY. These guidelines are effective upon receipt, however, all LLWAS sited under earlier draft siting criteria will remain certifiable until resiting is completed.

7. SITE ADAPTATION. Regional site adaptation that deviate from these guidelines shall be cleared through the FAA Technical Center, Flight Information Systems Branch, ACN-230.

8. REPORTS. LLWAS site locations will be reported to the National Flight Data Center (NFDC), ATO-250, in accordance with Order 7900.2A, Reporting of Electronic Navigation Aids and Communication Facilities Data to the NFDC.

for Alvin J. Thomas

Robert E. Brown
Director, Program Engineering Service

APPENDIX 1. GENERAL SITING CONSIDERATIONS

1. INTRODUCTION

The effectiveness of the Low Level Windshear Alert System (LLWAS) is dependent not only on the reliability of the electronic equipment but also the location of the wind sensors and their electronic packages. Adherence to the guidelines for sensor geometry in Appendix 2 and for siting with respect to obstructions and terrain in Appendix 3 will insure that the LLWAS operates as designed. Improper siting of the wind sensors will create false alarms and significantly degrade the performance of the wind shear algorithm. A properly sited system will accurately detect, identify and locate wind shear events, including microbursts, and provide a reasonable estimation of the wind component affecting aircraft performance. The present requirement is for 6 to 22 or more wind sensors on or around an airport. The number varies with the number of runways and their length.

2. GENERAL CONSIDERATIONS

The methodology in designing an LLWAS installation at an airport must include consideration for the optimum performance of the system:

a. Maintain the required geometry for the sensor array.

b. Adhere to spacing requirements.

c. Minimize the influence of terrain and obstructions.

3. LOGISTICAL CONSTRAINTS

Logistical constraints that are considered important are:

a. Penetrations of FAR Part 77 surfaces, Terminal Instrument Procedures (FAA Directive No. 8260.3B) surfaces, and Airport Design Standards surfaces per Advisory Circulars Nos. 150/5300-2C, 150/5300-4B, and 150/5300-12 by the placement of poles in the vicinity of an airport. Prior to installation, an airspace study must be accomplished to maintain/determine possible effects on protected surfaces for existing and planned instrument approach procedures to associated runways.

b. Line of sight for radio link between remote and master station antennas.

c. Current location of wind sensors at those airports adding or resiting sensors.

d. Access to the site.

e. Property ownership/lease of proposed site.

f. Proximity of AC power.

g. Proximity of strong signal generating equipment.

h. Proximity of high voltage power lines which can create electromagnetic interference.

i. Security of site from vandalism.

j. Lightning protection and grounding requirements.

k. Proximity to sheltering obstructions.

l. Subsurface evaluations.

m. Proximity to planned improvements or development in the vicinity.

4. AN APPROACH TO SITING LLWAS

The sequence of steps that follow is a suggested approach to siting LLWAS:

a. Using appendix 2, lay out a proper geometry. ACN-230 will provide initial layout for those airports with an installed LLWAS.

b. Adjust layout for obvious terrain and obstruction problems (use aerial photographs and topographical maps).

c. Select several candidate locations for each wind sensor site.

d. As appropriate, coordinate candidate site locations with local airport authority, National Weather Service and Air Traffic Service offices. Design layouts using candidate sites.

e. Check each layout for adherence to geometry and spacing guidelines.

f. Survey sites for detailed terrain and obstruction data using appendix 3.

g. Compute required pole heights.

h. Adjust for logistical constraints enumerated in paragraph 3 above. These are not prioritized in order to allow regions freedom in addressing site-unique situations.

i. Prepare final design layout.

APPENDIX 2. GEOMETRIC CONSIDERATIONS IN THE SITING OF LLWAS

1. INTRODUCTION

The original Low Level Windshear Alert System (LLWAS) has been enhanced for the detection of microburst and windshear events and has several additional capabilities. These improvements will now be known as the LLWAS Network Expansion. To achieve these improvements, more care will be taken in the design of an LLWAS station geometry at an airport.

There are three major tasks for the new LLWAS Network Expansion:

(1) Detect, identify, and locate microburst and windshear events along and near the runways;

(2) Estimate the runway component of wind speed loss resulting from a microburst windshear event.

(3) Sense and report centerfield and approach/departure winds.

Studies show that any geometry that is satisfactory for the identification of microbursts is also satisfactory for the detection of general windshear events. However, to obtain accurate runway component estimates, there is less freedom in the design of the station geometry, especially with regard to the distance of the stations from the runway centerline.

Generally speaking, there is a great deal of latitude in the design of the geometries for the detection and identification of windshear events. Unfortunately, not only are the requirements for the runway component estimations more strict, but when they are violated, the accuracy of the estimations degrades rather rapidly. While it is difficult to quantify these effects, guidance is given in section 2.

2. GENERAL PRINCIPLES

The Network Expansion LLWAS algorithm detects windshear by applying statistical principles to the wind data from the entire network. The algorithm identifies microburst events by estimating wind field derivatives from data from the vertices of triangles, which are formed by the station positions. The triangle geometry is also used for the estimation of the runway component of wind speed loss/gain. These algorithms and the geometries, for which they give the best results, have been analyzed theoretically and have been extensively tested by computer simulation. Operational testing was conducted during August 1987 at Denver, CO.

Aircraft are most vulnerable to a microburst encounter while on the runway and during departure and final approach. The LLWAS allocated protection region is that portion of the flight path inside of the middle markers, and this discussion is confined to the detection of microbursts and windshear events on that portion of the runway path. For a 10,000 foot runway and with a 2,500 foot extension at either end of the runway, the total length of the protected path is 15,000 feet.

Pilots desire a reliable estimate of the headwind loss/gain that they can expect to encounter along their runway path; this loss/gain is called the runway component of the windshear. It is used as an estimate of the severity of the expected impact of a microburst/windshear on their operations. This product will be available from a properly sited LLWAS, during the Network Expansion phase of the program.

A microburst located with its center only a short distance to either side of the aircraft flight path can have a significant adverse effect on aircraft performance. This effect is most pronounced when the microburst center is within 2,500 feet of the centerline of the flight path. One design goal for LLWAS is to detect any microburst whose center is within 2,500 feet to either side of the centerline of a runway and its extension to the middle marker (approximately 2,500 feet from the end of the runway). For a typical runway that is 10,000 feet long, this means that a rectangular region 15,000 feet long and 5,000 feet wide needs to be protected. This protection region is indicated in figure 2-1.

Since the winds are nearly calm at the center, a microburst whose center nearly coincides with a station is very difficult to detect by this sensor and most likely will be detected by an adjacent station. If the stations are properly sited, then it is unlikely that there will be a delayed detection of a hazardous microburst. On the other hand, the radius of the strong outflow of a microburst can be as small as 5,000 feet. Therefore, if the stations are placed too far apart, it is possible for a microburst to occur between the stations and not be observed until the microburst outflow reaches a station. If the station spacing is no larger than 8,500 feet, then most microbursts that occur in the network will be promptly detected. The runway component estimations are also severely degraded when the microburst center is near a station in a "blind spot". These "blind spots" extend approximately one-eighth of the way to the nearby stations; for example, if the stations are 8,000 feet apart, then the "blind spots" are approximately disks of radius 1,000 feet.

3. THE DESIGN OF THE LLWAS GEOMETRY FOR AN AIRPORT

Most airports have several runways. LLWAS protects the airport when it protects each runway. Economies can be achieved by choosing the stations sites so that some stations provide protection to more than one runway. If this were not done, then an airport with two runways would require twelve stations, an airport with three runways would require eighteen stations, etc. By designing for shared use of sensors, airports might be protected with as few as eight or nine stations (Figures 2-2 and 2-3). These examples also illustrate acceptable relaxation of the strict design guidelines that are given in this section.

When trying to design an improved LLWAS installation for a complex airport that has an existing LLWAS installation, the combination of attempting to achieve multiple uses of the stations and to make use of existing stations may lead to designs where more than six stations are involved in protecting some runways.

The initial problem at most LLWAS airports will be resiting some or all of the original six anemometers to achieve optimum coverage for the runways while facilitating the siting of additional sensors. Figure 2-4 shows six stations providing coverage for three runways. Later when three more stations are added full coverage will be realized. The guiding concept in resiting any of the original six stations is to preclude having to resite any of these stations when additional sensors are installed.

3.1 THE PROTECTION OF RUNWAYS

In this section, a procedure is provided for designing a station geometry that protects runways. Some allowable practical variations are discussed.

Reliable and timely microburst detection and identification is a fundamental requirement of LLWAS. To obtain satisfactory performance, it is advisable to keep the stations approximately 2,500 to 3,000 feet to either side of the runway path. The system will perform satisfactorily most of the time if a station is as close as 1,000 feet from the runway path. If a station is less than 1,000 feet from the runway path, then there can be microbursts centered on the runway path for which detection may be significantly delayed.

To achieve reliable runway component estimates, the design requirements are more stringent than those for microburst detection and identification. If the stations are placed between 2,500 and 3,000 feet to either side of the runway path, then runway components can reasonably be estimated. If the design departs significantly (<2,000 feet or >3,500 feet) from this guideline, then there can be microbursts which impact the runway, and for which the runway component estimates are significantly in error. For example, stations placed 3,500 to 4,000 feet from the runway can lead to underestimations of the runway components by as much as 15 to 20 knots. When stations are placed closer to the runway, underestimations of similar magnitude are to be expected in the "blind spots".

It is also important that the protection region be covered by the triangle pattern. With the nearly regular triangles specified, the entire region inside of each triangle is protected, except for the "blind spot" near the station. In addition, a rectangular region is protected along each edge of a triangle. This region extends along the edge to within one-eighth of the distance to each endpoint and 1,000 feet to either side of the edge. In particular, it is again the "blind spots" that are not covered. The covered region is indicated in figure 2-5.

3.1.2 THE PROTECTION OF A SINGLE RUNWAY

In this section, a graphical procedure is shown in figure 2-1 for designing a station geometry that protects a single runway. Parallel runways which have their centerlines less than 2000 feet apart are treated as single runways.

3.1.3 THE PROTECTION OF PARALLEL RUNWAYS

In this section, a graphical procedure is shown in figure 2-8 for designing a station geometry that protects parallel runways. Parallel runways are defined as a pair of runways whose centerlines are greater than 2000 feet apart.

3.1.4 THE PROTECTION OF DIAGONAL RUNWAYS

An example is seen for the diagonal runway in figure 2-3. Figure 2-6 shows the stations protecting this diagonal runway, the triangle pattern, and the "blind spots" for this diagonal runway. In this case, the basic principles regarding station spacing, triangle shape, and distance of the stations from the runway apply.

3.2 DESIGN METHODOLOGY

An effective design of a station geometry for the protection of an airport can be obtained as follows.

STEP 1: DRAW THE PROTECTION REGION FOR EACH RUNWAY.

The protection region is a rectangle that extends 2,500 feet beyond each end of the runway and 2,500 feet to each side of the centerline of the runway (see figure 2-1). Rectangular patterns are most effective but are not imperative.

STEP 2: SELECT THE STATION POSITIONS.

The following conditions should be satisfied:

(1) Stations should be between 2,000 and 3,500 feet to either side of the runway.

(2a) The spacing between adjacent stations along the runway should be greater than 3,280 feet but less than 7,550 feet.

(2b) For airports that will also have a Terminal Doppler Weather Radar (TDWR), the spacing between adjacent stations along the runway should be greater than 3,280 feet but less than 9,500 feet.

(3) The triangles formed by nearby stations should be fairly regular, i.e., no triangle should have an angle smaller than 25 degrees or greater than 135 degrees.

(4) Designate one site, the most central part of

the airport, as the centerfield wind sensor. It is advisable to keep the centerfield wind sensor at least 1,000 feet away from all runways.

(5) Number stations starting at the designated centerfield wind sensor (1) and then clockwise from north through northwest.

STEP 3: DETERMINE THE "BLIND SPOTS" AND THE PROTECTED AREAS.

It is possible to graphically estimate the size and shape of the "blind spots". Using the fact that the "blind spot" extends approximately one-eighth of the distance along each edge of a triangle, we have the following graphical procedure:

(1) Draw the triangle pattern.
(2) Mark the one-eighth distance positions on the edges of the triangles.
(3) Roughly sketch the perimeters of these "blind spots".
(4) Sketch areas protected by the edge rectangles (1,000 feet beyond the edge and between the "blind spots", see Figure 2-5).

Then the overlap of the "blind spots" with the protection region for the runway is the area where hazardous microbursts may not be detected in a timely manner. Significant underestimations of the runway components can be expected in regions that are approximately one and a half times as large as the "blind spots".

STEP 4: DETERMINE THE PORTION OF THE PROTECTION REGION THAT IS UNPROTECTED.

This area is the portion of the protection region that is either inside of a "blind spot" or is not covered by the pattern of station triangles and edge rectangles. The unprotected portion of the protection region should be shaded.

STEP 5: USE THE GRAPHICAL DISPLAY OF THE UNPROTECTED PORTION OF THE AIRPORT TO DETERMINE IF THE COVERAGE IS SATISFACTORY.

This is a question of judgement, based on knowledge of the difficulty of the problems for this airport.

With this design, any microburst, whose center is within the unshaded portion of the protection region will be detected in a timely manner with high probability. If the stations lie within or close to the 2,000 to 3,500 foot strip, then the runway component estimations will be acceptably accurate. One acceptable design, the Ideal Station Geometry, is shown in figure 2-1.

To illustrate the shading of the unprotected part of the protection region (step 4), we considered a case that is typical of many existing LLWAS installations. Figure 2-7A shows a station near the center of the runway and 'middle marker' stations at the ends of the runway. Figure 2-7B shows an enhancement that has been obtained by adding another station near runway center. Figure 2-7B also shows the consequence of the shading (step 4). **Note** that there will be delayed detections of microbursts at the runway ends and close to runway center.

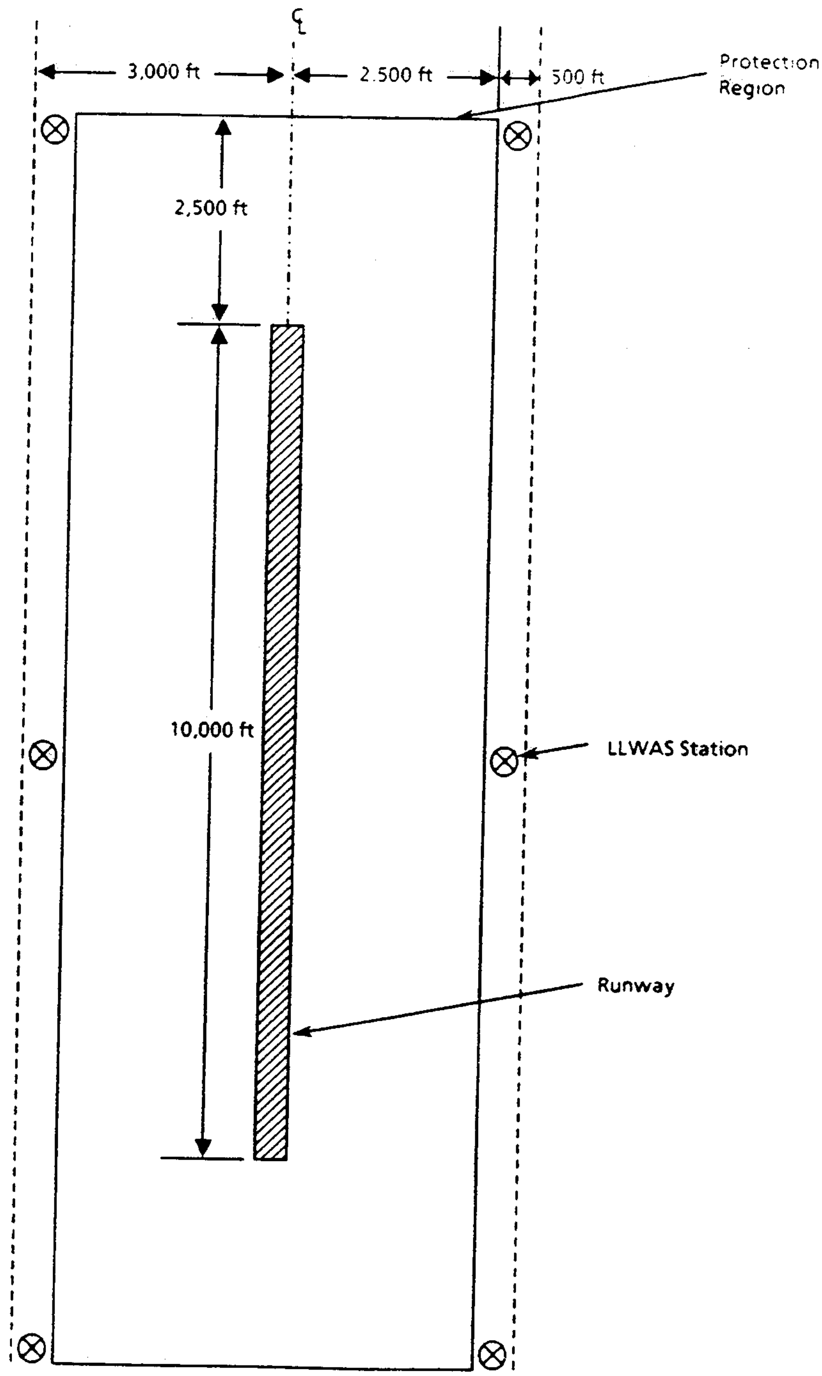


FIGURE 2-1. IDEAL GEOMETRY FOR THE DETECTION OF MICROBURST WINDSHEAR ALONG A RUNWAY

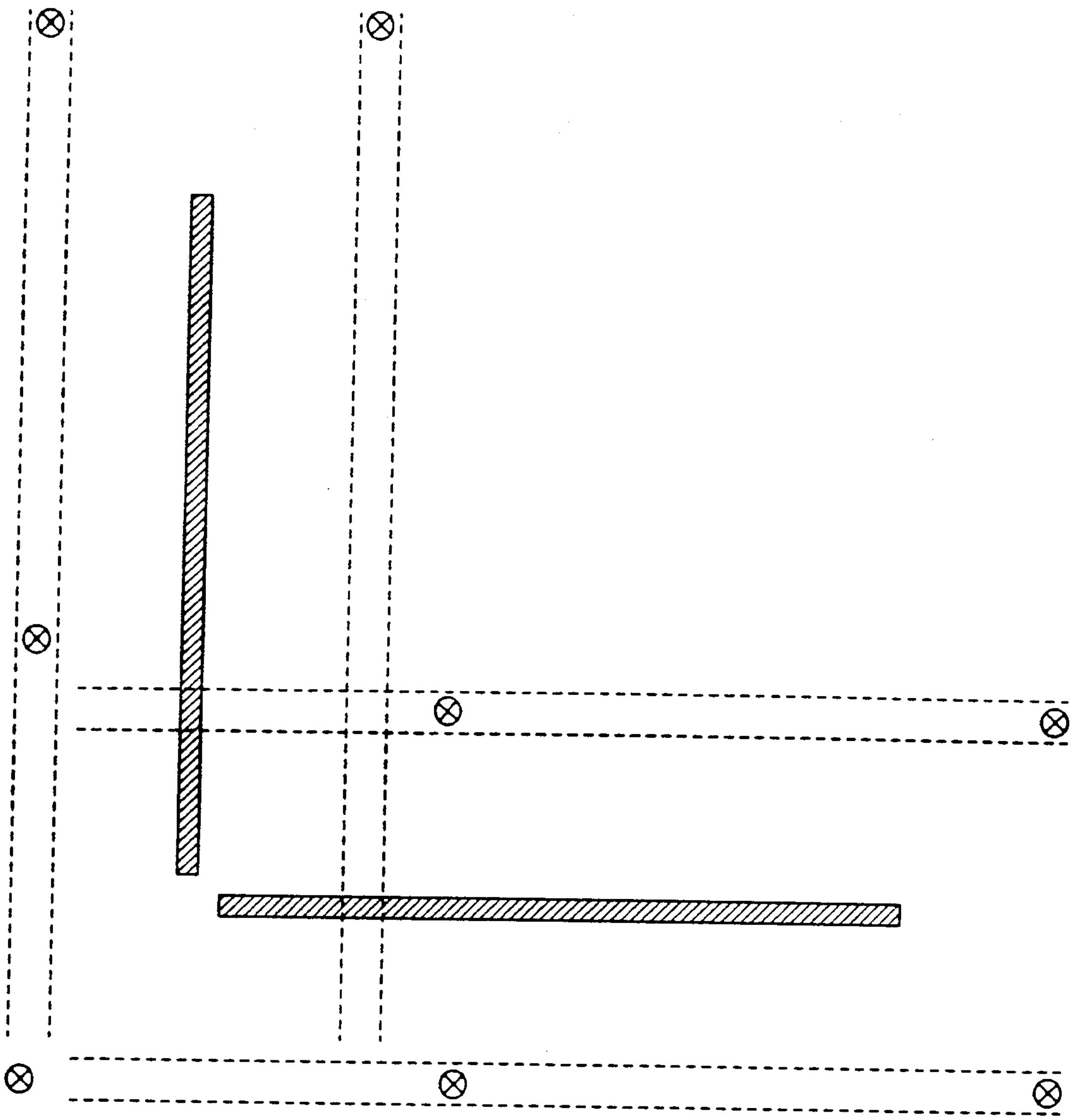


FIGURE 2-2. LLWAS DESIGN FOR AN AIRPORT WITH TWO RUNWAYS

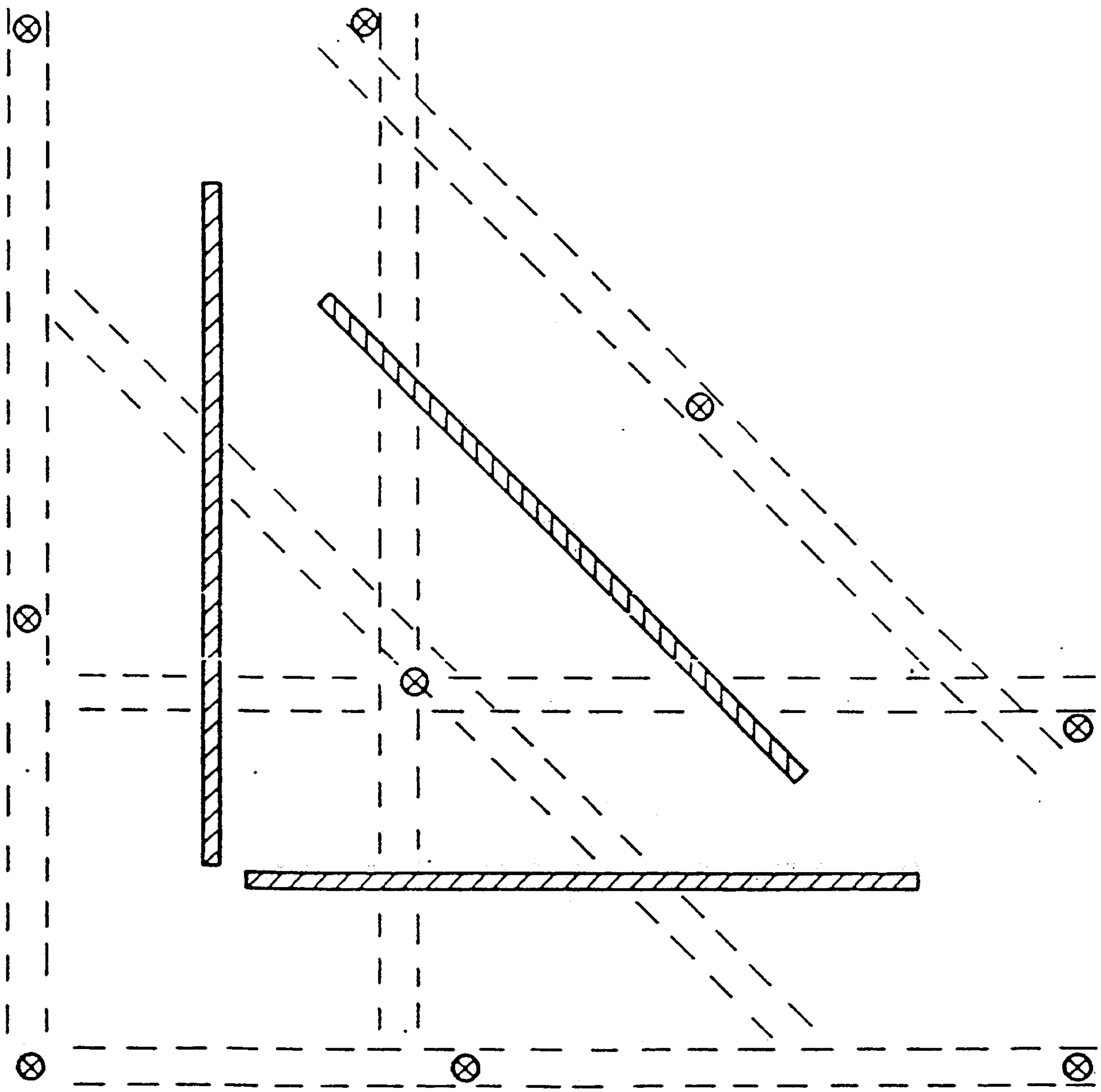


FIGURE 2-3. LLWAS DESIGN FOR AN AIRPORT WITH THREE RUNWAYS

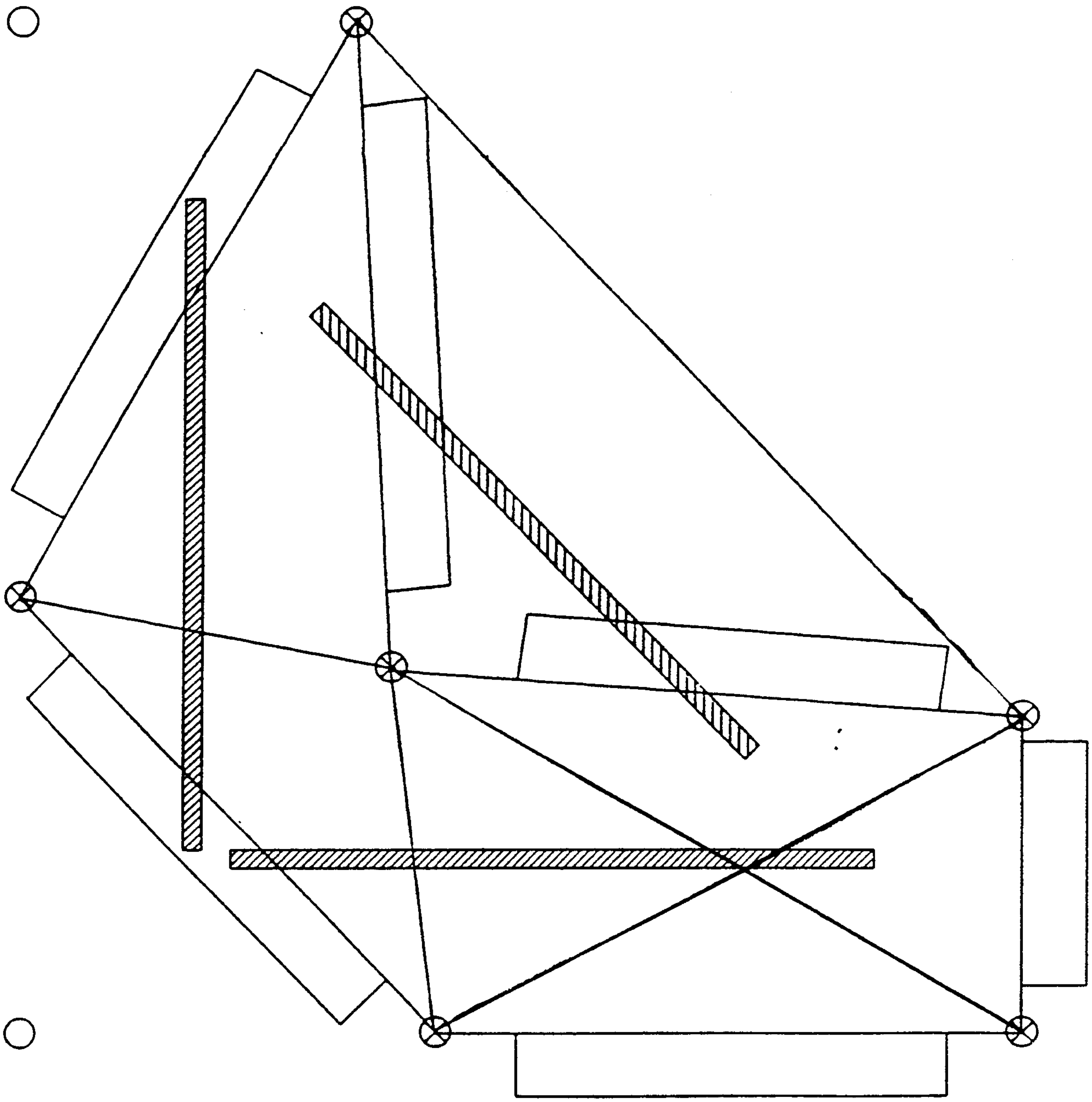


FIGURE 2-4. LLWAS DESIGN FOR SIX STATIONS COVERING THREE RUNWAYS (**NOTE** THAT THE SIX STATIONS ARE SITED TO FACILITATE FUTURE EXPANSION)

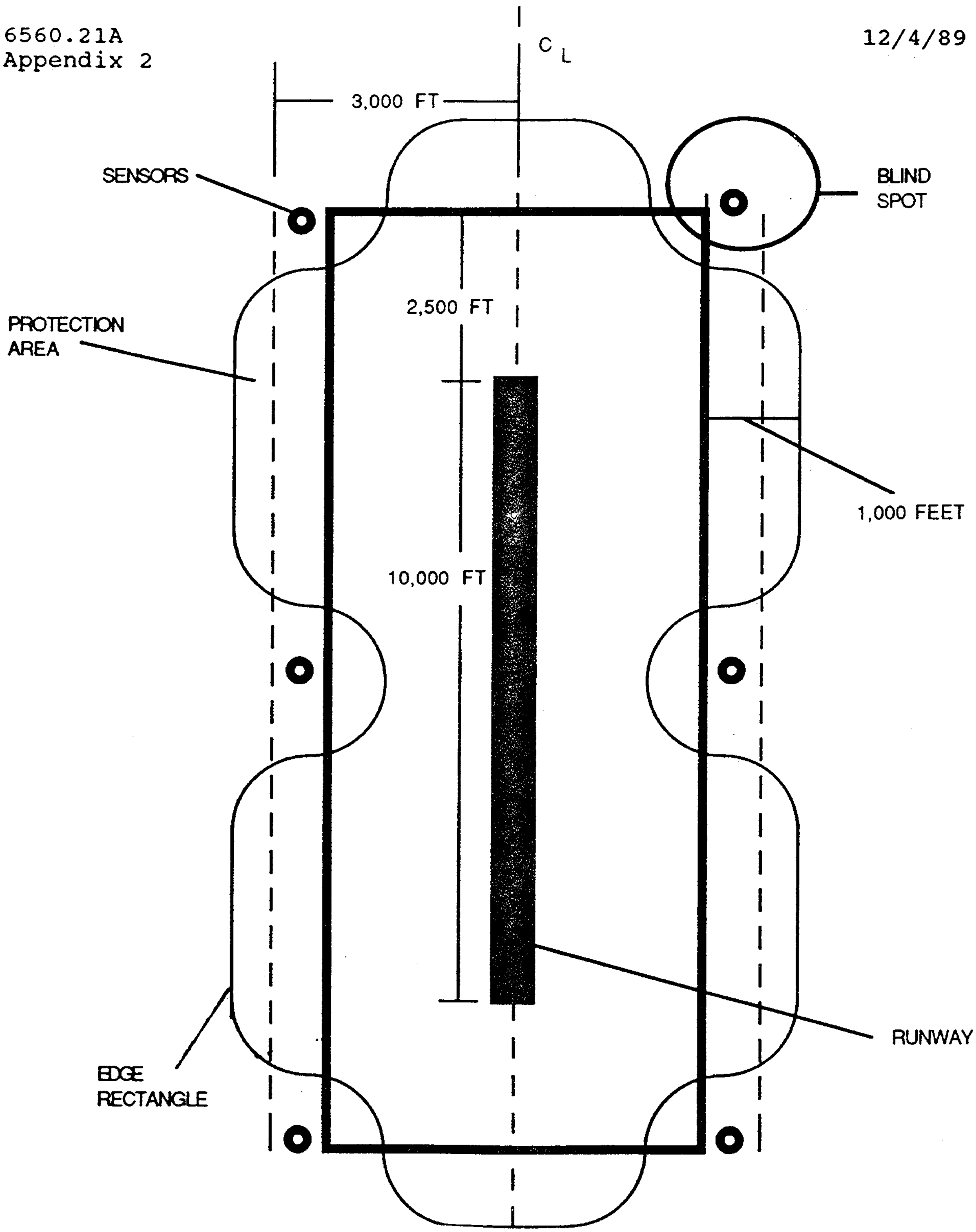


FIGURE 2-5. SIX STATIONS PROTECTING A SINGLE RUNWAY SHOWING BLIND OR DEAD SPOTS

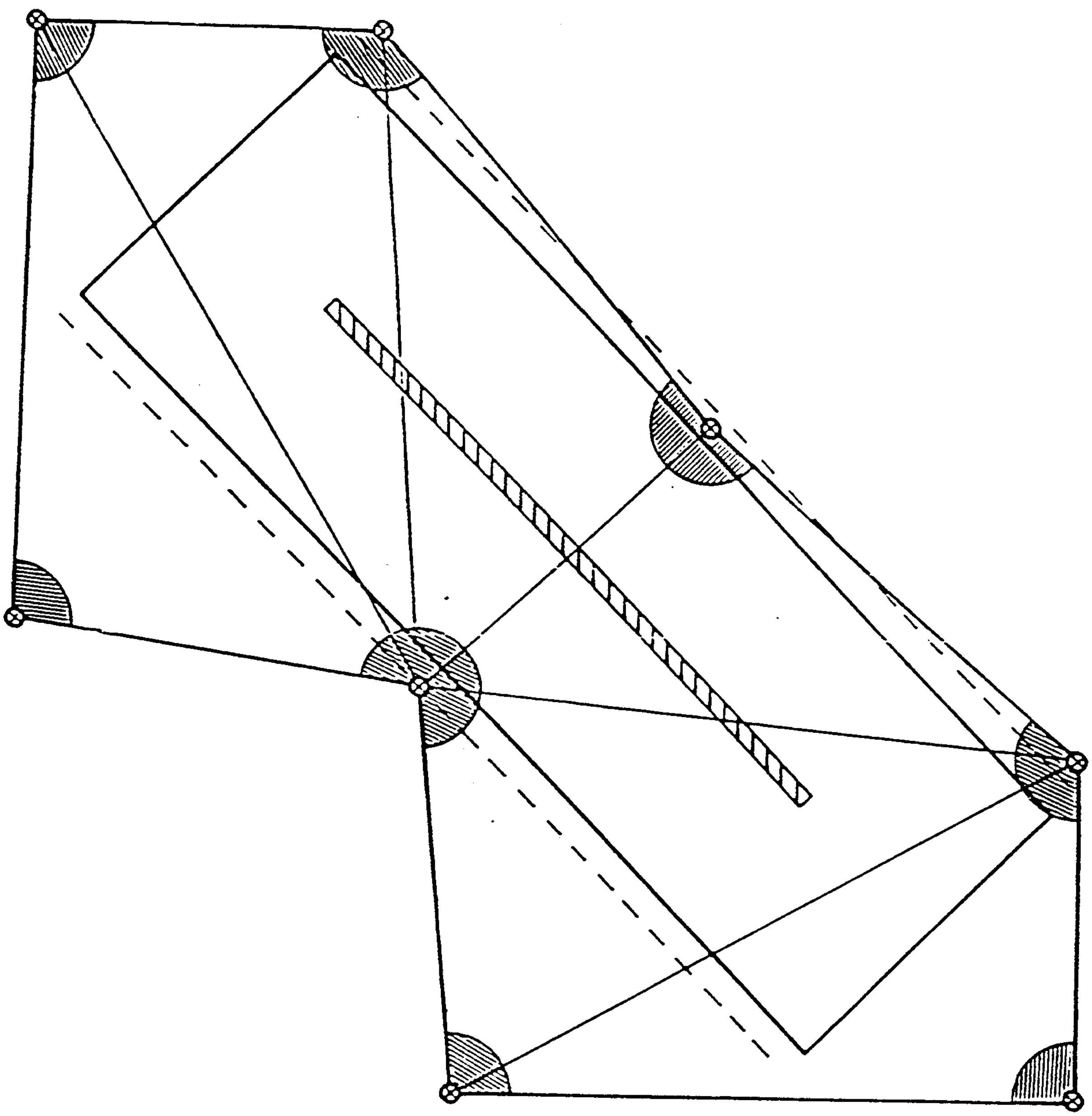
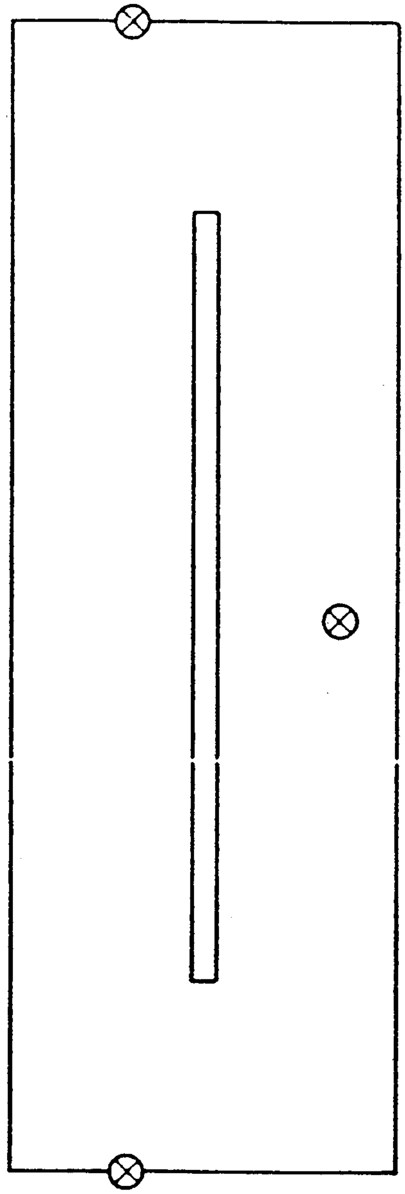
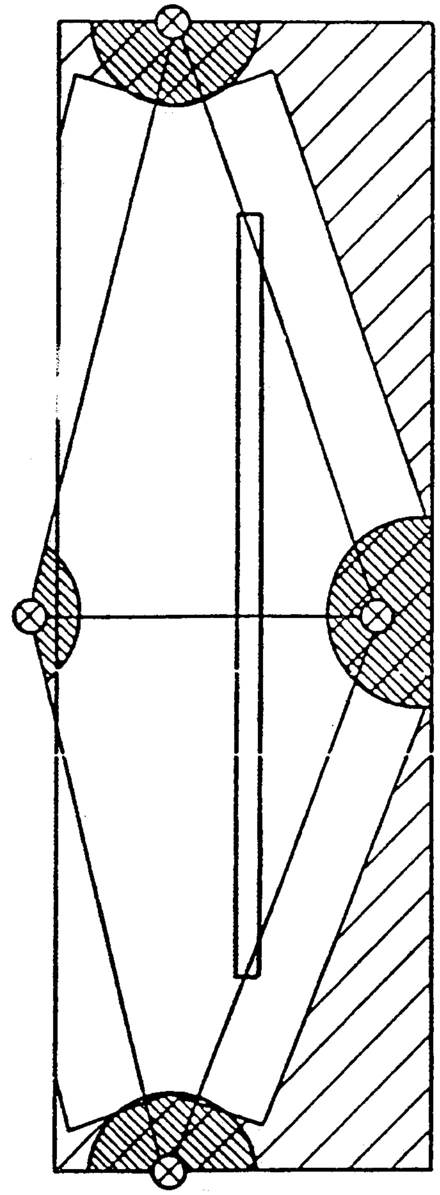


FIGURE 2-6. EIGHT STATIONS PROTECTING THE THIRD RUNWAY SHOWN IN FIGURE 2-3; TRIANGLE PATTERN AND BLIND OR DEAD SPOTS ARE SHOWN



a) Basic LLWAS



b) Network Expansion LLWAS

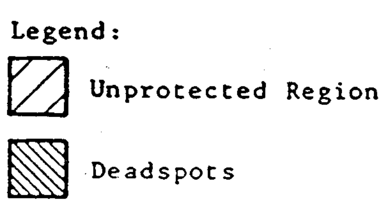


FIGURE 2-7. APPLICATION OF SHADING IN THE PROTECTED REGION

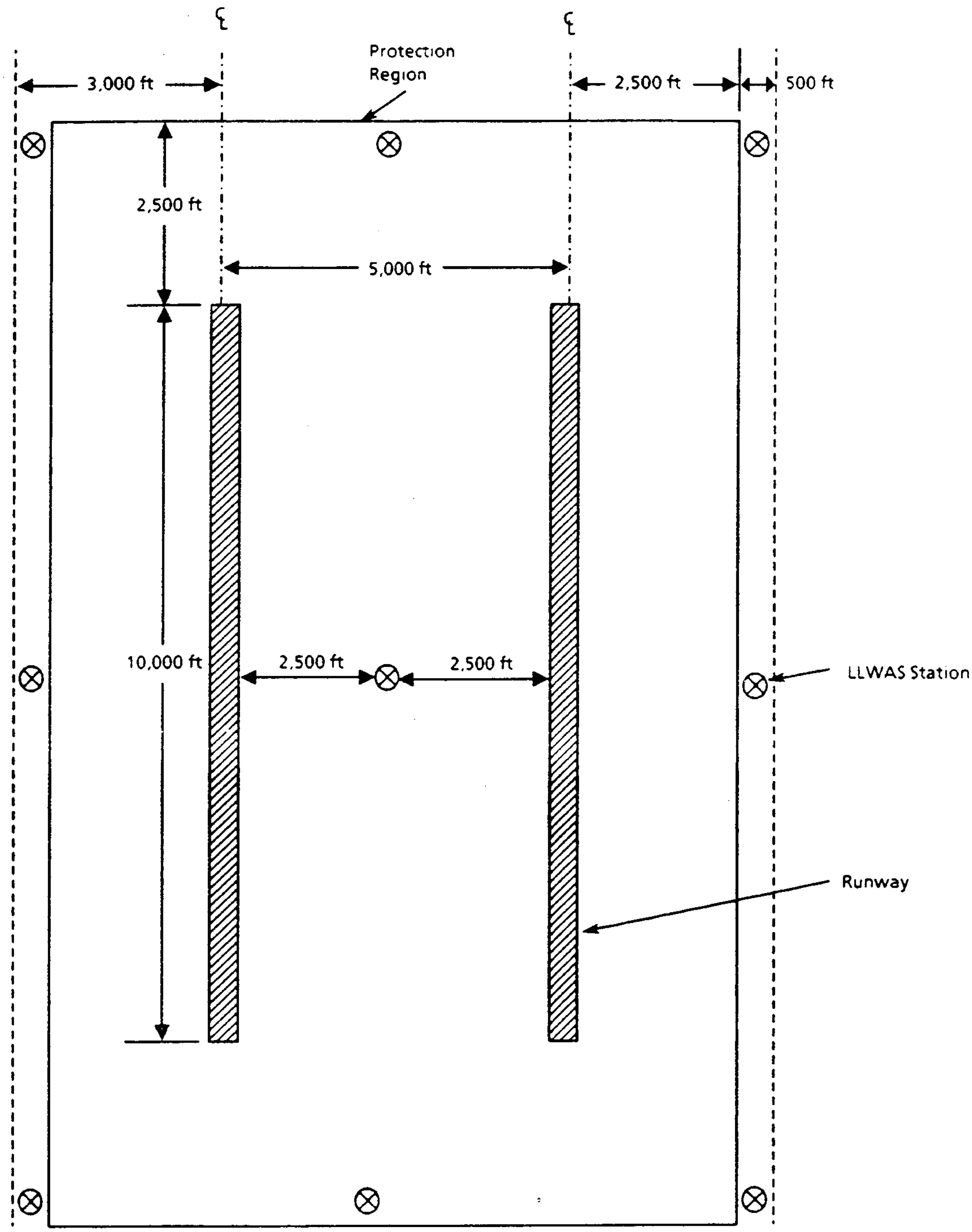


FIGURE 2-8. PROTECTING PARALLEL RUNWAYS

APPENDIX 3. GUIDELINES FOR SITING INDIVIDUAL LLWAS ANEMOMETERS

1. INTRODUCTION

This appendix provides the rationale and supporting criteria for siting individual anemometers. Step-by-step procedures are included and specific examples with a sample format are provided.

2. GENERAL CONSIDERATIONS

The procedures used in siting individual anemometers (after the geometric layout has been determined) also must include consideration for the optimum performance of the system:

a. The least sheltered anemometer is the standard against which sheltering at others is evaluated.

b. Sheltering at an anemometer from all effects should not exceed twenty (20) percent.

c. Insure that the mounting supports do not block the anemometer. The structure on which the anemometer is mounted should be reduced to a minimum to prevent local wakes or flow accelerations from impinging on the anemometer. Care should be taken to insure that warning lights, etc. are not placed on the same level as the anemometer and that lightning rods are of a small diameter ($\leq$1.5") and located at an adequate distance ($\geq$18.0") from the propeller of the anemometer.

d. Units must be consistent when taking measurements and doing calculations.

e. When unique situations at an individual anemometer site arise that are not covered by these criteria, then assistance should be requested from the FAA Technical Center, Surveillance and Weather Systems Branch, ACN-230.

3. SITING PROCEDURES AND CRITERIA

This section provides criteria and supporting information and outlines a step-by-step procedure for siting individual anemometers. Specific examples with a suggested format and a list of notations and terms are included at the end of this section. It is important to be able to properly identify the obstruction(s).

3.1 Three-Dimensional Obstacles

Three-dimensional obstacles include single trees, groups of trees, individual buildings, groups of buildings, hangars, fuel or water tanks, or billboards. Three dimensional obstacles have a width of less than ten times their height.

3.1.1 Computing the Percent Sheltering

The following measurements are needed from the obstacle geometry; (1) X, distance from obstacle, (2) H, obstacle height, and (3) W, obstacle width. The parameter α, know as the power-law exponent, defines the roughness of the environment between obstacle and the anemometer (see table 3-1).

The velocity deficit represented by $(u_0-u)/u_0$ is the fractional sheltering or specified error in wind measurement due to sheltering by an obstacle. A graphical procedure to estimate $(u_0-u)/u_0$ is shown in figures 3-1 and 3-2 for open country (α=0.15) and suburban (α=0.25) environments, respectively.

Example:

Given Measurements: H = 120 ft, W = 200 ft, X = 960 ft, H/W = 0.6, and X/H = 8.

Solution: Since an open-country environment is anticipated for a site, Figure 3-1 will be used. Enter the top graph of Figure 3-1 at H = 120 ft. Move right to the 0.6 curve for H/W. Move down to the lower graph on vertical line to X/H = 8. Move left to read 18% for error.

3.1.2 Computing the "Reduced Distance" X_R From an Obstacle

Figure 3-3 provides a means for selecting a "reduced distance" X_R from an obstacle at which an anemometer may be installed at any desired height with a desired specified error, $(u_0-u)/u_0$.

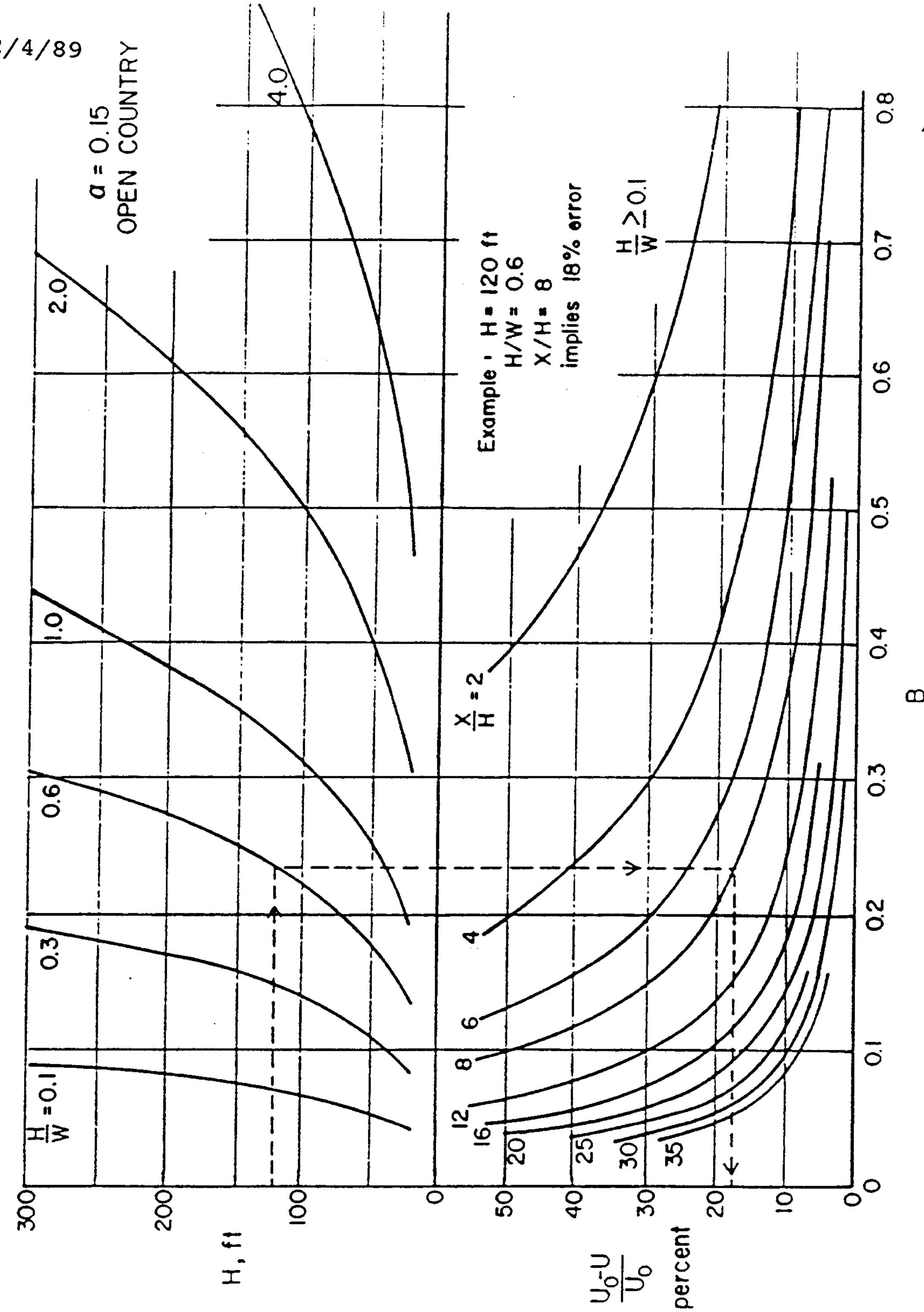


FIGURE 3-1. SELECTION CHART FOR SHELTERING FOR A THREE-DIMENSIONAL OBSTACLE IN AN OPEN COUNTRY ENVIRONMENT

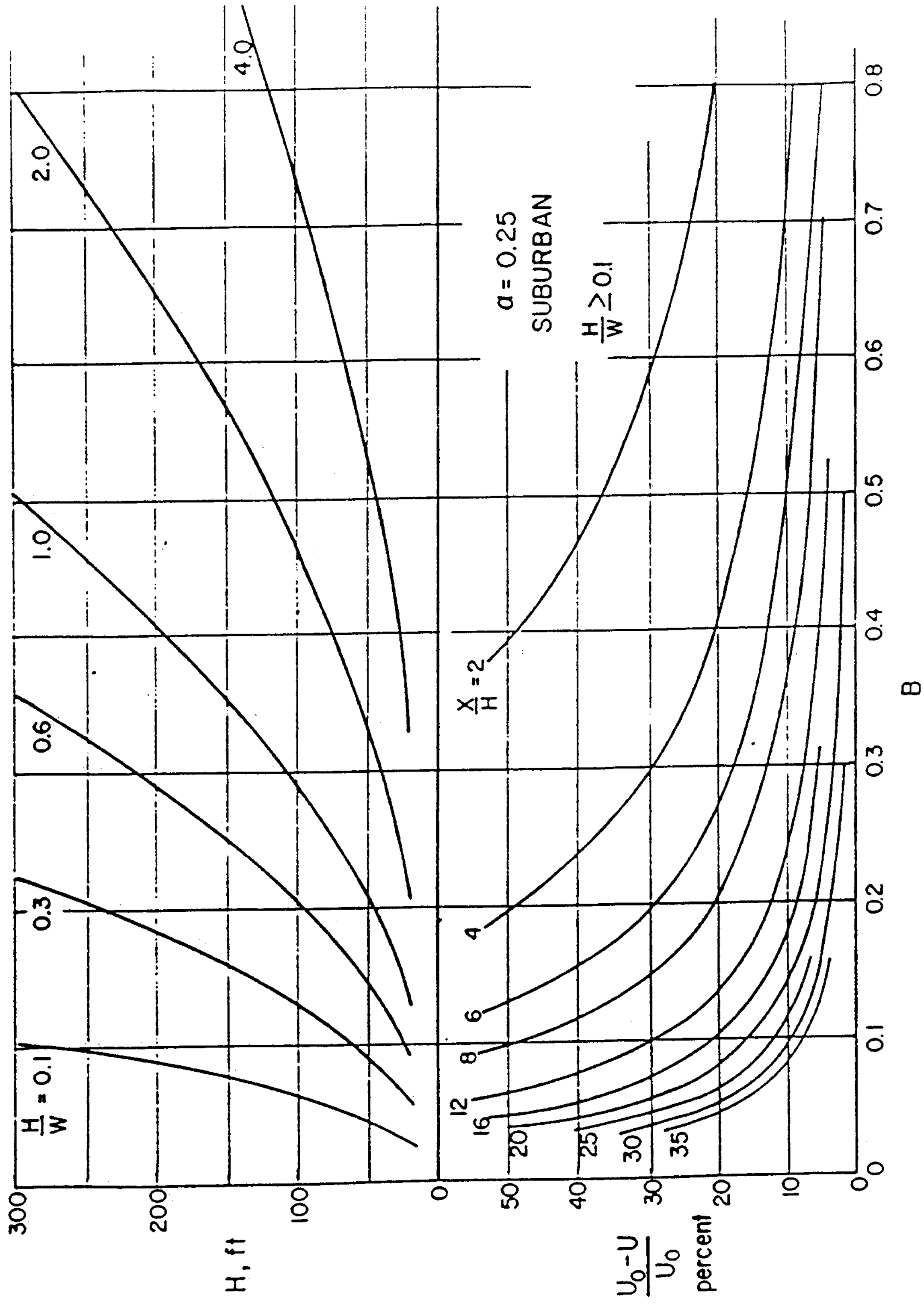


FIGURE 3-2. SELECTION CHART FOR SHELTERING FOR A THREE-DIMENSIONAL OBSTACLE IN A SUBURBAN ENVIRONMENT

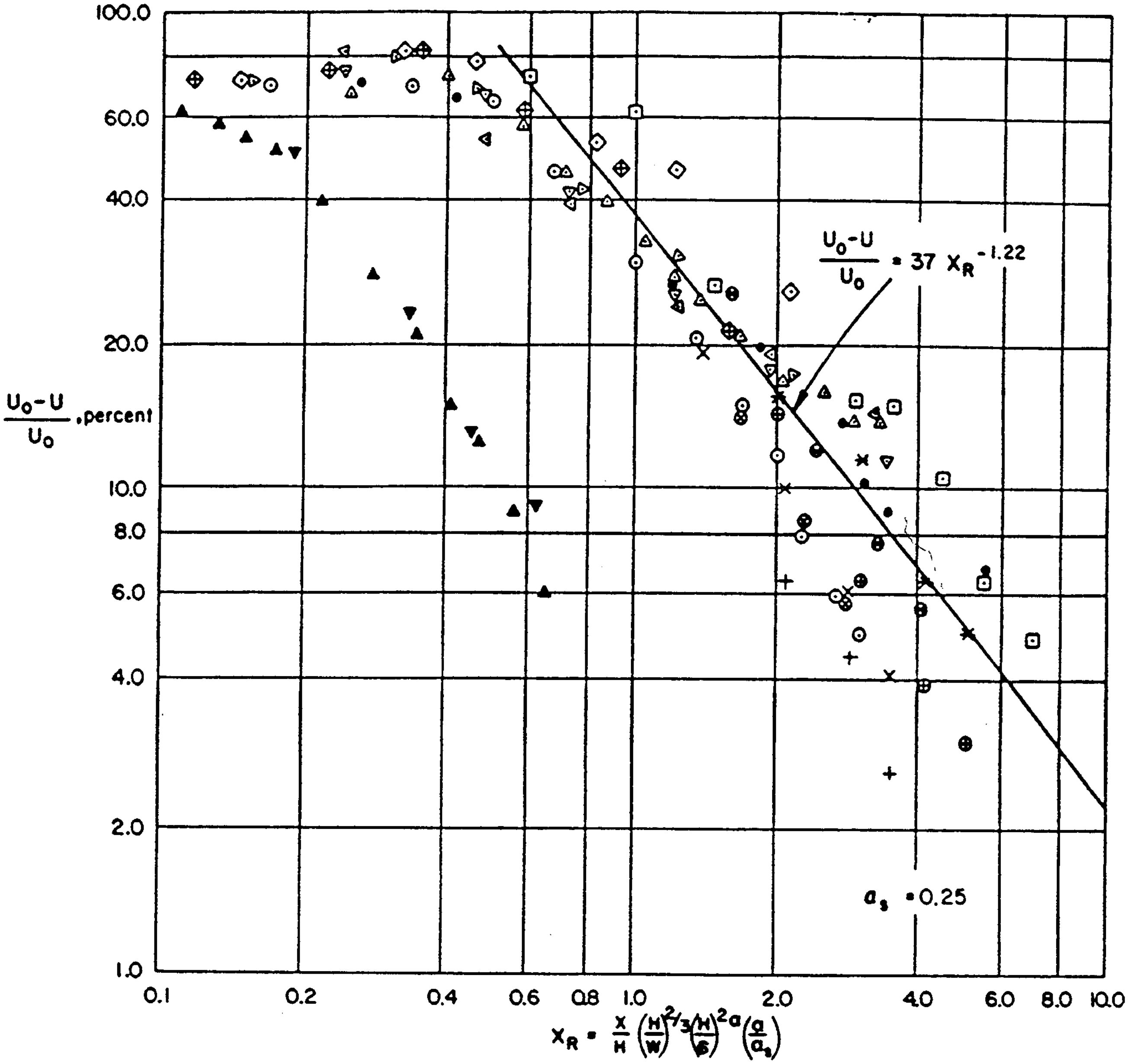


FIGURE 3-3. VARIATION OF MAXIMUM VELOCITY DEFICIT WITH REDUCED DISTANCE FOR THREE DIMENSIONAL OBJECTS

3.1.3 Computing Optimal Anemometer Height

In some situations it may be necessary to alternatively consider the height of a sensor for acceptable error when the anemometer must be placed sufficiently close to the object (in the wake) that acceptable errors cannot be obtained at an arbitrary elevation using the method described above. It is first necessary to compute the "reduced distance" X_R.

Step 1 Compute δ by:

$$\delta = 367 + 3333\alpha$$

Where δ, the boundary layer thickness, is in feet and α, the power-law exponent, is estimated from Table 3-1.

Step 2 Compute X_R by:

$$X_R = \left[\frac{X}{H}\right]\left[\frac{H}{W}\right]^{\frac{2}{3}}\left[\frac{H}{\delta}\right]^{2\alpha}\left[\frac{\alpha}{\alpha_s}\right]$$

For X, distance from obstacle, H, barrier height, W, barrier width, δ from Step 1, α from table 3-1, and α_s equals 0.25 (typical suburban power-law exponent).

Step 3 Figure 3-3 provides the contours of equal error $(u_0-u)/u_0$ in percent form as a function of X_R and Z/H. Once a X_R is obtained, enter figure 3-4 to determine an acceptable elevation (Z/H) for the anemometer. Either contours (curves) or suggested zones (rectangular) may be used. Example, if $X_R=1.2$, then for 20% sheltering, Z/H=2.00.

3.2 Two-Dimensional Obstacles

Two-dimensional obstacles include fences, rows of trees, hedges, long buildings, or bridges. Two-dimensional obstacles have a height/width of less than 0.1, where the width is perpendicular to the wind.

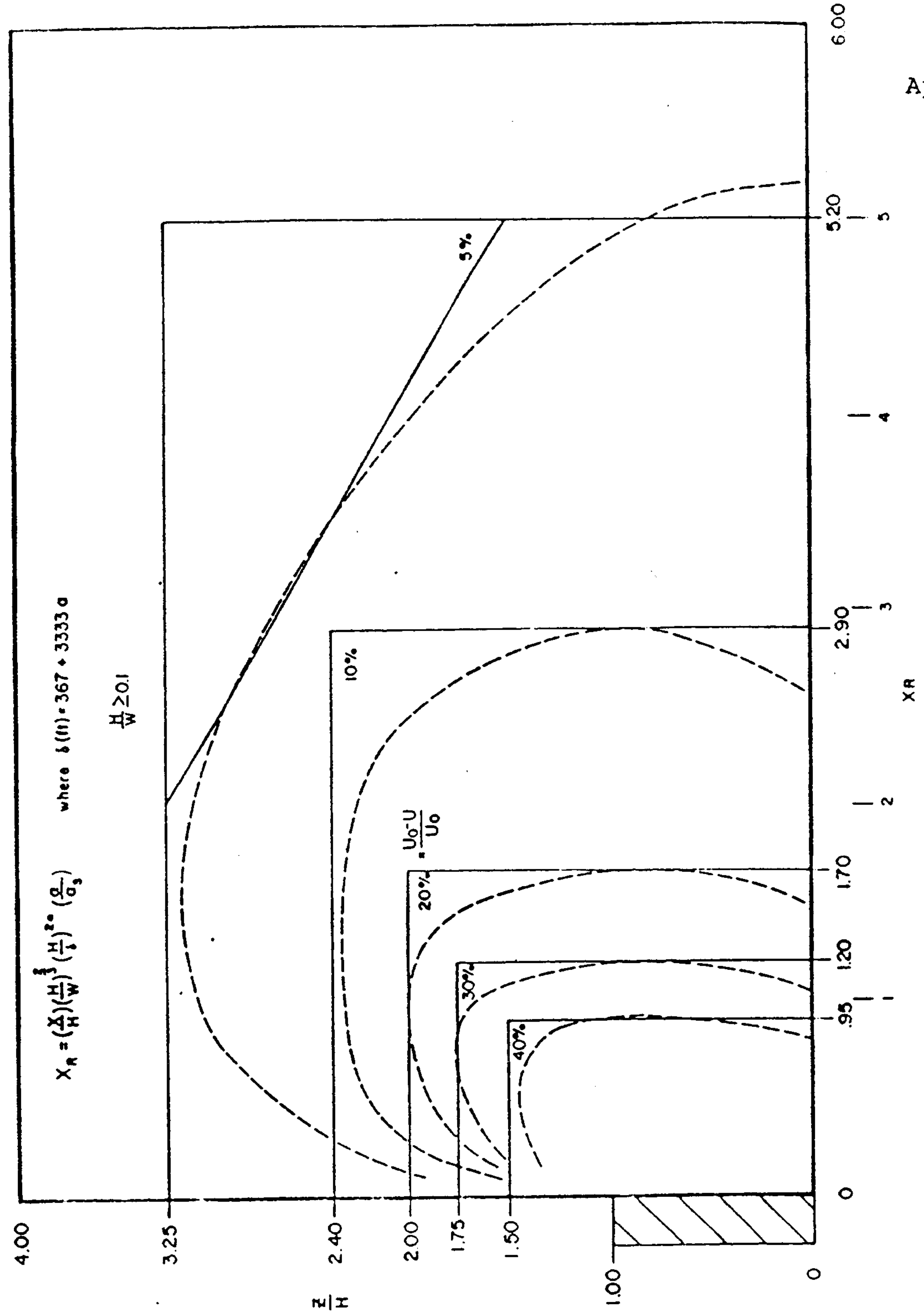


FIGURE 3-4. CONTOURS OF EQUAL ERROR IN VELOCITY IN THE WAKE OF A THREE-DIMENSIONAL OBSTACLE

TABLE 3-1. ESTIMATED VALUES OF THE SURFACE ROUGHNESS

z_0 (roughness length)	Representative Value Meters	Terrain	α (power-law exponent)
0.5-1.5	0.7	Center of large towns, cities, forests	0.35
		Dense forests of relatively non-uniform height	0.27-0.30
		Dense forests of relatively non-uniform height	0.23-0.25
0.15-0.5	0.3	Small towns, suburban area	0.24
0.05-0.15	0.1	Wooded country villages, out-skirts of small towns, farmland	0.20
0.015-0.05	0.03	Open country with isolated trees and buildings	0.17
0.007-0.015	0.01	Grass, very few trees	0.15
0.0015-0.007	0.003	RUNWAY AREAS (avg.) Surface covered with snow, rough sea in storm	0.13
< 0.0015	0.001	Calm open sea, lakes, snow covered flat terrain. Flat desert.	0.11

3.2.1 Computing the Percent Sheltering

The following measurements are needed from the obstacle geometry; (1) X, distance from obstacle, and (2) H, obstacle height.

Low Obstacles: $$\frac{(u_o - u)}{u_o} = 2000 \left[\frac{X}{H} \right]^{-1.5} \quad \text{for } H \leq 100 \text{ ft}$$

High Obstacles: $$\frac{(u_o - u)}{u_o} = 4300 \left[\frac{X}{H} \right]^{-1.5} \quad \text{for } H > 100 \text{ ft}$$

3.2.2 Computing Optimal Anemometer Height

In situations where the placement of the anemometer must be closer to the obstacle than the distance required by these equations (i.e. in the wake) then the anemometer may be raised to a sufficiently high elevation.

Step 1 Compute X/H.

Step 2 Figure 3-5 provides the contours of equal error $(u_o-u)/u_o$ in percent form as a function of X/H and Z/H. Either contours (curves) or suggested zones (rectangular) may be used. Once X/H is calculated, enter Figure 3-5 to determine an acceptable elevation (Z/H) for the anemometer. Example, if X/H=12, then for a 20% sheltering, Z/H=1.7.

3.3 Forest Canopies

A forest canopy is define as a grouping of trees (from the perspective of the Remote Station) that is more than 700-800 feet wide and more than 300 feet deep. Otherwise, it is classified as either a three-dimensional or two-dimensional obstacle.

3.3.1 Computing Optimal Anemometer Height For Wind Speeds Above a Forest Canopy (Long Fetch)

Where a forest extends upwind from the Remote Station for a distance B at least 100 times the average tree height, a procedure assuming that the boundary layer above the forest has reached equilibrium is used.

Figure 3-6 provides a plot of the ratio of the velocity u_r at height z_r above the mean forest height d over the rough (r) forest surface, to the velocity u_s at height z_s (which might be 20 ft) above a smooth (s open field unaffected by obstructions.

This ratio is plotted in figure 3-6 for comparison with an anemometer in the smooth open terrain at an elevation of 20 feet. A reasonable guide to values of α_r are:

$0.24 \leq \alpha_r \leq 0.25$	For dense forest of relatively uniform height on smooth height.
$0.26 \leq \alpha_r \leq 0.27$	For dense forest of relatively non-uniform height or breaks on smooth terrain.
$0.28 \leq \alpha_r \leq 0.29$	For dense forest of relatively non-uniform height or with breaks on rough terrain.

This procedure should overestimate anemometer heights if the length of forest is short, $B/d < 100$.

Example: Given: select an anemometer height in a forest environment on smooth terrain where tree heights are relatively uniform and where average tree height d = 50 ft. Assume the anemometer is to read not more than 20% less than an open-country anemometer at 20 feet.

Solution: from Figure 3-6, select $\alpha_r = 0.24$ and move vertically to $u_r/u_s = 0.8$. Read $z_r = 45$ ft. Therefore, the elevation of the anemometer above ground should be $d + z_r = 95$ ft.

3.3.2 Computing Optimal Anemometer Height For Wind Shelter Downwind of a Forest Canopy (Long Fetch)

Downwind of a forest area, over an open field, the boundary layer recovers from that over the forest to that over an open field. Very little data have been found in the literature for this case. Because of the small number of cases available in the literature, wind tunnel tests were run to provide additional data for these criteria.

Data obtained from the wind-tunnel simulation of 64 forest wakes are summarized in figure 3-7 to show the decrease in anemometer error with distance from the forest and height of the anemometer above ground. The figure shows that the height required to obtain a particular error remains similar to that at the downstream edge of the forest (see figure 3-7) for a distance Xn of 0.025 before decreasing with additional downwind distance.

Example: Given: at a distance X downwind of a forest of length B = 1000 ft with trees of roughly uniform height averaging d = 30 ft, find the anemometer height required to provide an error of no more than 20% in comparison to the same site with unlimited upwind exposure of the same roughness (i.e., no forest). The site is in an open grassy field. Solve for X = 100, 500, or 800 ft.

Solution:

Step 1 Compute Xn,

$$Xn = \frac{X/B}{1.0 + 274\ (d/B) + 1.4\ \mathrm{LN}\ (Z_1/Z_0)}$$

From Table 3-1, let $\alpha_1 = 0.24$, $Z_1 = 0.3\text{m}$, and $Z_0 = 0.01$.

Step 2 Figure 3-7 provides the contours of percent error as a function of Xn and z/d. Either contours (curves) or suggested zones (piecewise straight lines) may be used. Once Xn is calculated, enter figure 3-7 to determine an acceptable elevation (z/d) for the anemometer. From figure 3-7 for 20% error:

For X = 100ft	Xn =.007	z/d = 2.0	z = 60ft
500	.036	1.7	51
800	.057	any	any

3.4 Surface Roughness Changes

When the wind flows from a region with a particular surface roughness, z_o1, to a region with a different surface roughness z_o2, there is change in the shape of the velocity profile near the ground, up to height $h_I(x)$, see figure 3-8. The layer below $h_I(x)$ is often called the Internal Boundary Layer (IBL). The height $h_I(x)$, which increases with the distance X from the roughness interface, is called the height of the IBL.

Clearly, two anemometers placed at the same height, but at different distances from an interface, would not record the same wind speed. Abrupt changes from an urban terrain to a smooth terrain, or visa versa, are also associated with local accelerations or wakes caused by the change of the effective level of the ground.

The purpose of this section is to present a convenient algorithm for estimating the approximate magnitude of changes in winds speeds downstream of such interfaces.

3.4.1 Computing Optimal Anemometer Height For Single Step Change in Roughness

The equations describing the wind field across the internal boundary layer for a single roughness change are:

$$\frac{u(z)}{u_1\,(10)} = \left[\frac{z}{10}\right]^{\alpha_1} \qquad \text{for } x \le X_o1$$

and

$$\frac{u(z)}{u_1\,(10)} = b_{10}\left[\frac{z}{10}\right]^{\alpha_1+\beta} \cdot x^k \qquad \text{for } x > X_o1$$

where

$$X_o1(z) = \left[b_{10}\,(z/10)^{\beta} \right]^{-\frac{1}{k}}$$

In these equations, $u(z)$ is the velocity at height z a distance x downwind of the roughness change (figure 3-8); $u_1(10)$ has been selected as a reference velocity upwind of the roughness change at an elevation of 10 m; α_1 is the upstream value of roughness described as a power-law exponent; and b_{10}, β, and k are obtained from table 3-2.

The above equations can be solved for the value of z as a function of $u(z)/u_{10}$.

$$z = 10 \left[\frac{u(z)}{u_1(10)} \right]^{\frac{1}{\alpha_1}} \qquad \text{for } x \le X_o1$$

$$z = 10 \left[\frac{1}{b_{10}} \; \frac{u(z)}{u_1(10)} \; \frac{1}{x^k} \right]^{\frac{1}{\alpha_1+\beta}} \qquad \text{for } x > X_o1$$

where

$$\frac{u(z)}{u_1\ (10)} = \left[\frac{z}{10} \right]^{\alpha_1} \qquad \text{for } x \le X_o1$$

$$\frac{u(z)}{u_1\ (10)} = b_{10} \left[\frac{z}{10} \right]^{\alpha_1+\beta} \cdot x^k \qquad \text{for } x > X_o1$$

Thus knowledge of only four parameters, b_{10}, $(\alpha_1+\beta)$ and k, is required for determining the height of the sensor for a prescribed velocity difference tolerance, i.e., $u(z)/u_1(10)$. Application of equations for Z are based on computed value of X_o1. Representative values of surface roughness and the corresponding power law exponent α are given in table 3-1.

TABLE 3-2. VALUES OF COEFFICIENTS B_{10}, β, AND k.

Z_{01}=	Z_{02}=	0.001	0.003	0.010	0.030	0.100	0.300	0.700
	a_1 \ a_2	0.107	0.126	0.147	0.169	0.200	0.250	0.350
0.001	0.107				b_{10}= 1.105 β= 0.051 k =-0.032	b_{10}= 1.161 β= 0.088 k=-0.050	b_{10}=1.196 β =0.142 k=-0.069	
0.003	0.126				b_{10}= 1.093 β= 0.035 k=-0.025	b_{10}= 1.138 β= 0.072 k=-0.042	b_{10}= 1.155 β = 0.122 k=-0.060	b_{10}= 1.128 β =0.182 k=-0.075
0.010	0.147				b_{10}= 1.045 β = 0.012 k =-0.013	b_{10}= 1.093 β = 0.052 k=-0.031	b_{10}= 1.103 β = 0.101 k=-0.048	b_{10}= 1.059 β =0.167 k=-0.062
0.030	0.169	b_{10}= 0.911 β=-0.062 k = 0.029	b_{10}= 0.923 β=-0.051 k = 0.023	b_{10}= 0.960 β= -0.030 k = 0.012		b_{10} =1.053 β =0.029 k=-0.018	b_{10}= 1.064 β =0.076 k=-0.035	b_{10}=1.039 β = 0.144 k=-0.052
0.100	0.200	b_{10}= 0.916 β=-0.094 k = 0.040	b_{10}= 0.926 β=-0.084 k = 0.035	b_{10}=0.940 β=-0.065 k = 0.025	b_{10}=0.963 β=-0.039 k = 0.015		b_{10} =1.036 β = 0.049 k=-0.021	b_{10}= 1.014 β =0.111 k=-0.037
0300	0.250		b_{10}=0.929 β=-0.130 k = 0.050	b_{10}=0.950 β=-0.113 k = 0.040	b_{10} =0.958 β=-0.090 k = 0.031	b_{10}=0.996 β=-0.052 k = 0.015		b_{10}= 1.012 β = 0.062 k=-0.020
0.700	0.350					b_{10}= 1.035 β=-0.152 k = 0.030	b_{10}= 1.033 β=-0.099 k = 0.015	

Open blocks represent unavailable conditions in the data used to develop the table. For these cases, the nearest available condition may be used.

Note: B_{10}, β, and k are parameters derived from power law studies of roughness changes.

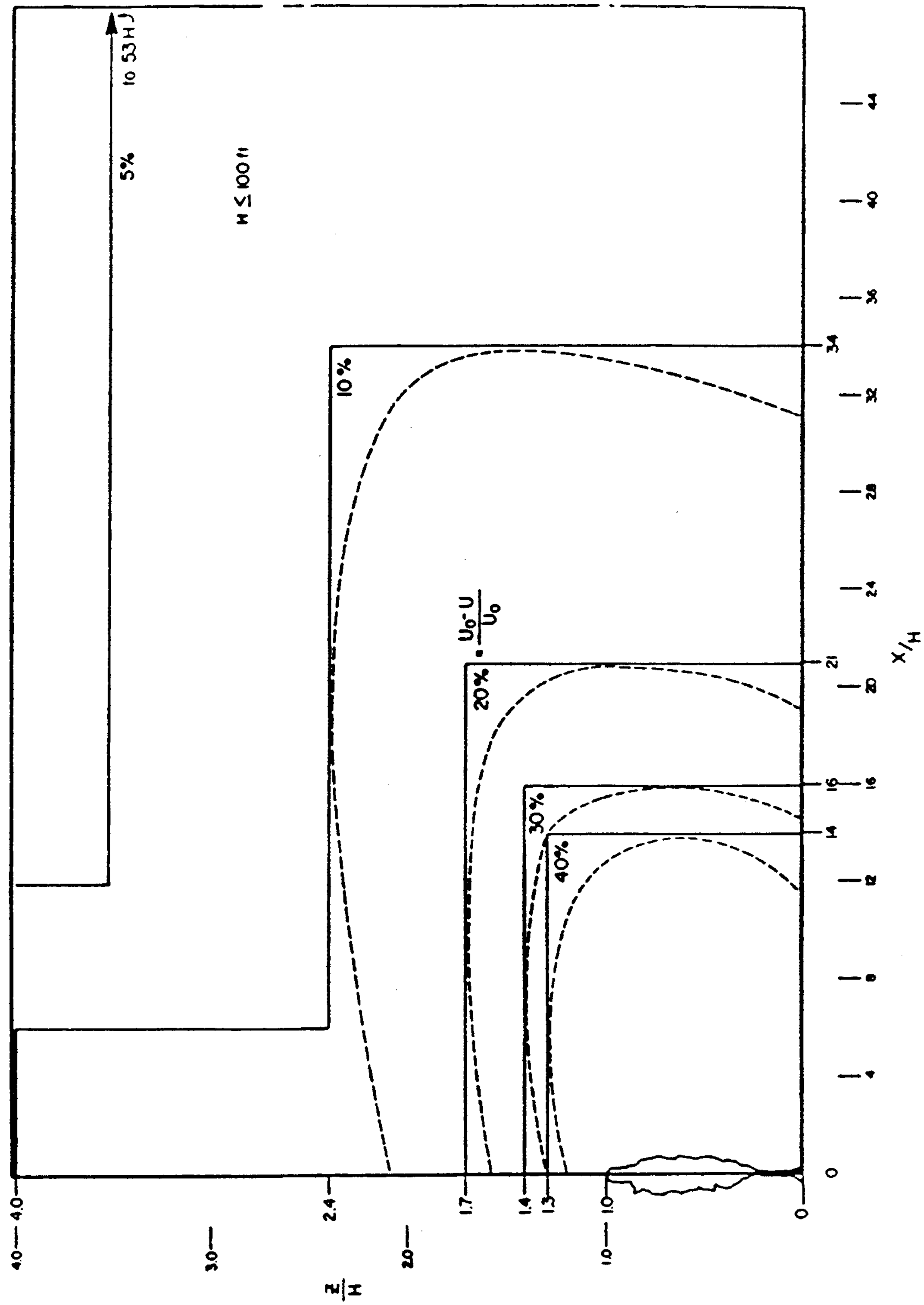


FIGURE 3-5. RECTANGULAR APPROXIMATIONS TO CONTOURS OF EQUAL ERROR IN VELOCITY IN THE WAKE OF TWO-DIMENSIONAL OBSTACLES

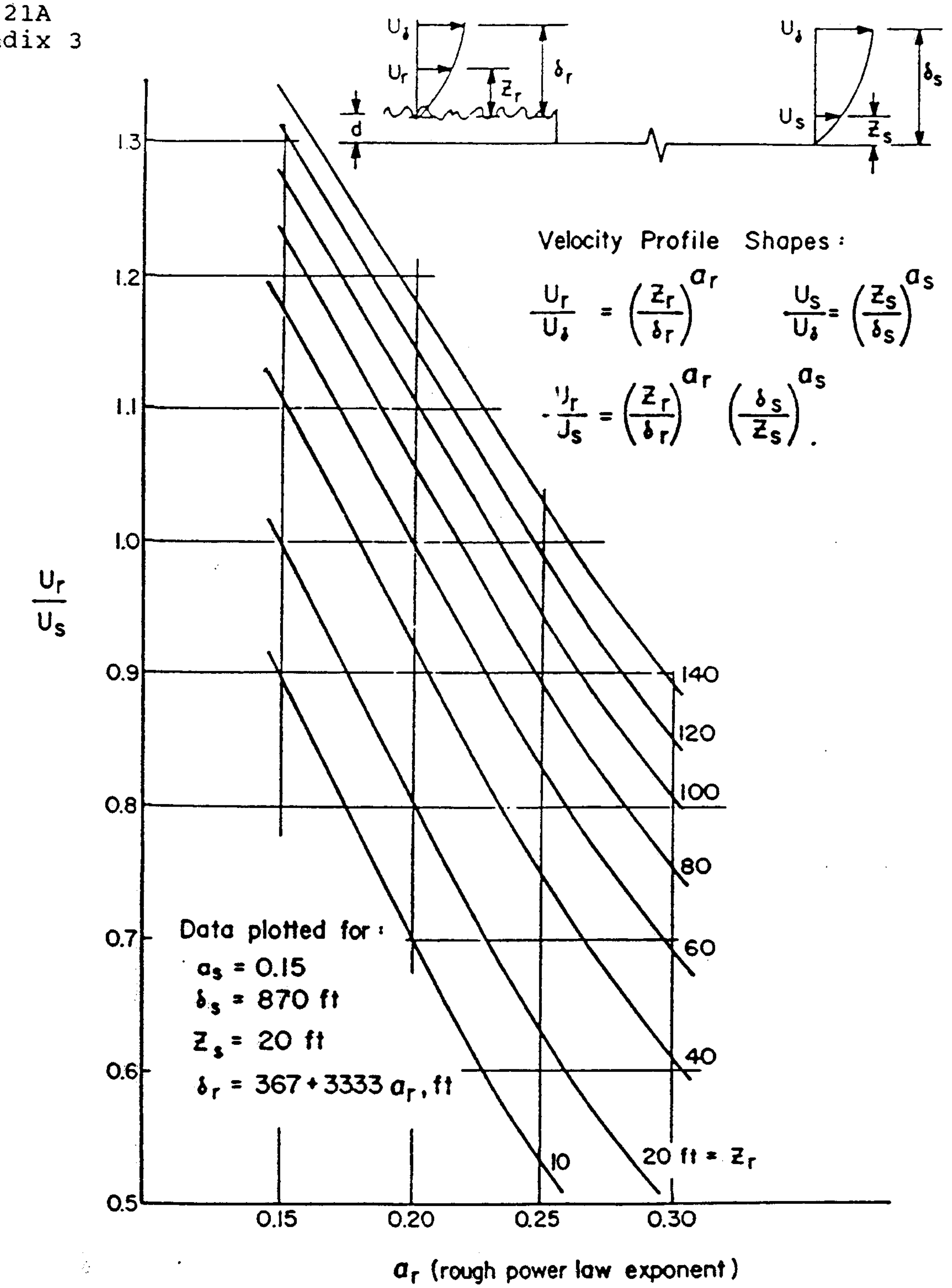


FIGURE 3-6. HEIGHT ABOVE ROUGH FOREST WHICH HAS SAME VELOCITY AS OPEN COUNTRY VELOCITY AT 20 FEET

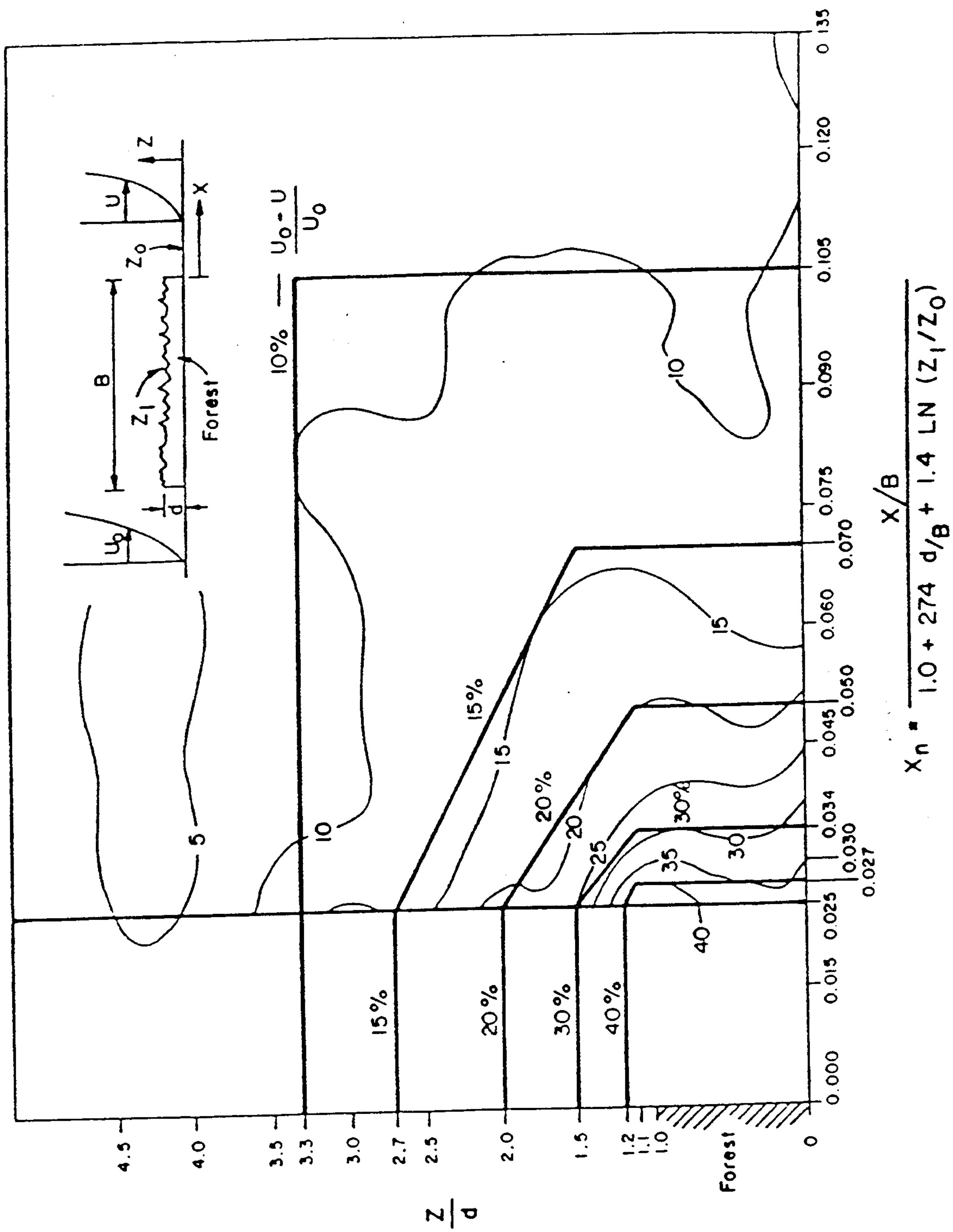


FIGURE 3-7. SHELTER DOWNWIND OF A FOREST

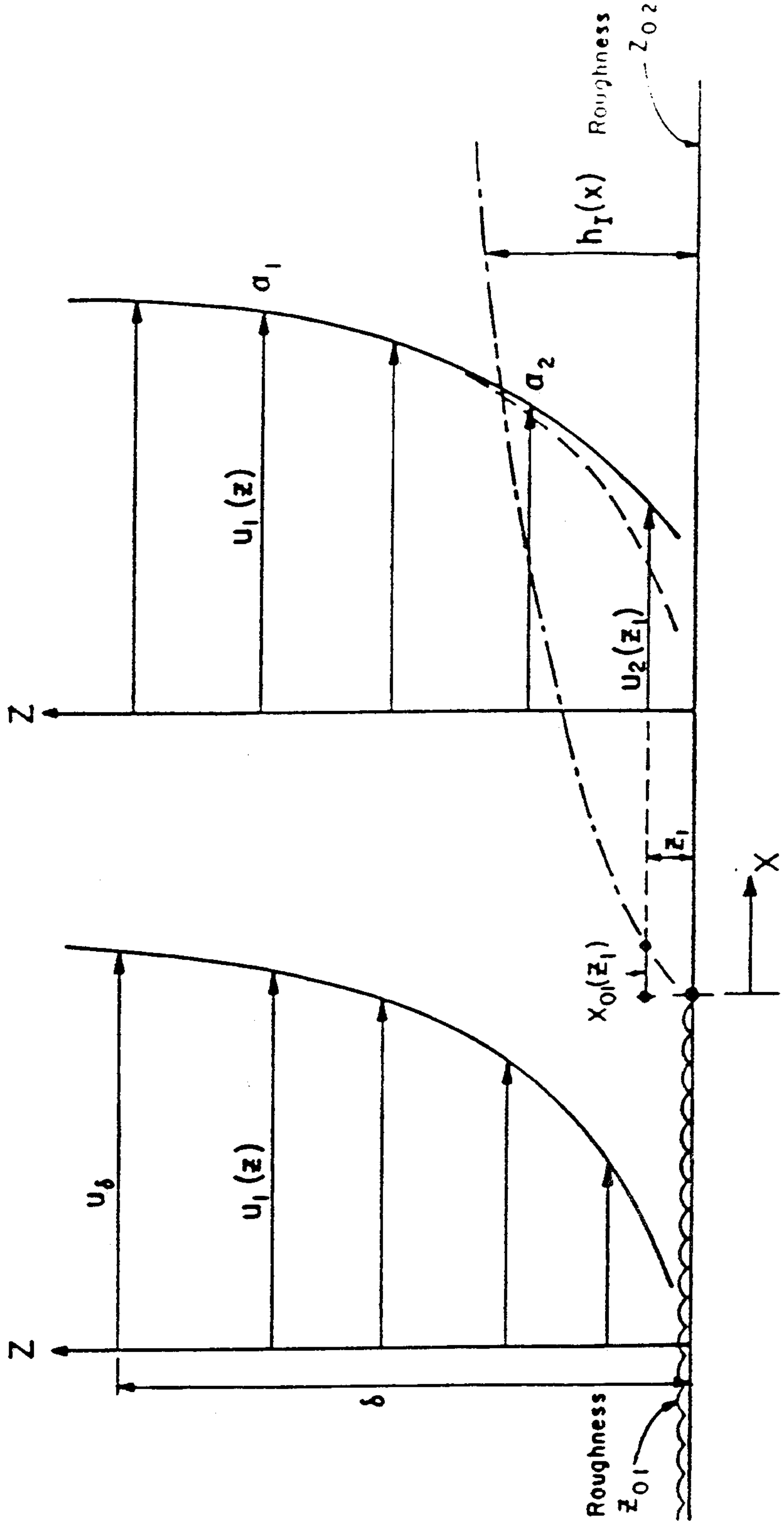


FIGURE 3-11. A SCHEMATIC DESCRIPTION OF THE INTERNAL BOUNDARY LAYER (IBL) AFTER A DECREASE IN SURFACE ROUGHNESS. **NOTE** THE INCREASED VELOCITIES WITHIN THE IBL. AT A GIVEN HEIGHT z_1, THE ROUGHNESS CHANGE IS EFFECTIVE DOWNWIND OF $X_{01}(z_1)$.

Example: (1) Given: $\alpha = 0.15$, $z_o1 = 0.01$ m, and $z_o2 = 0.3$ m
From Table 3-2: $b_{10} = 1.103$, $\beta = 0.101$, and $k = -0.048$

Let $\frac{z}{10} = 2$, $X_o1 = 33$ m

For $X < 33$ m;

$$\frac{u(z)}{u_{10}} = \left[2 \right]^{0.15}$$

Therefore, $\frac{u(z)}{u_{10}} = 1.11$

For $x > 33$ m;

$$\frac{u(z)}{u_{10}} = \left[1.103 \right] \left[2 \right]^{(0.147+0.101)} \left[X \right]^{-0.048}$$

Therefore, $\frac{u(z)}{u_{10}} = 1.31 \left[X \right]^{-0.048}$

If $X = 1000$ m, then $\frac{u(z)}{u_{10}} = 0.94$;

$X = 3000$ m, then $\frac{u(z)}{u_{10}} = 0.892$;

$X = 10000$ m, then $\frac{u(z)}{u_{10}} = 0.842$.

(2) Given: $\alpha = 0.35$, $z_o1 = 0.7$ m, and $z_o2 = 0.1$ m
From Table 3-2: $b_{10} = 1.035$, $\beta = -0.152$, and $k = 0.03$

Let $\frac{z}{10} = 1$, $X_o1 = 0.3$ m

For $X < 0.3$ m;

"this case is not of interest"

For $x > 0.3$ m;

$$\frac{u(z)}{u_{10}} = \left[1.035 \right] \left[1 \right]^{(0.35-0.152)} \quad \left[X \right]^{-0.048}$$

Therefore, $\frac{u(z)}{u_{10}} = 1.035 \left[X \right]^{0.03}$

If $X = 1000$ m, then $\frac{u(z)}{u_{10}} = 1.273$;

$X = 3000$ m, then $\frac{u(z)}{u_{10}} = 1.316$;

$X = 10000$ m, then $\frac{u(z)}{u_{10}} = 1.364$.

3.5 Terrain Effects Caused by 2-D Slopes and 3-D Slopes (Ridges and Hills)

Terrain effects include local hills, embankments, escarpments, valleys, and depressions. When accounting for the effects of terrain on the velocity profile, idealize the terrain into the forms shown in figure 3-10.

NOTE: This section is limited to single terrain features and small scale topographic configurations (small compared to the height of the atmospheric boundary layer). When considering multiple terrain features, assistance should be requested (see appendix 3 section 2(e)).

Consider the hill in figure 3-9. The approach velocity profile is designated by $u_a(z)$, where z is always the height above the local ground surface. The local velocities at other locations are designated by $u(x,z)$. The following equations are for the local speed-up (at the same z above the local ground surface);

a. velocity perturbation;

$$\triangle u(x,z) = u(x,z) - u_a(z)$$

b. fractional speed-up ratio;

$$\triangle S = \frac{\triangle u(x,z)}{u_a(z)}$$

c. amplification factor.

$$A = \frac{u(x,z)}{u_a(z)} = 1 + \triangle S(z)$$

The velocity field is determined by the exact geometric configuration of the terrain. The topographical configuration is described using two length scales.

a. h = The maximum height above the assumed horizontal upstream surface.

b. L = The typical length scale of the configuration. We shall adopt the commonly used definition of L, which is the distance from the crest where the elevation e above the environment is h/2.

In approximating the effect of a specific configuration, an estimate should be made of the appropriate values of h and L for which the analytical expression best describes the specific configuration, as shown for example in figure 3-10. Figure 3-10a shows a two dimensional ridge or a three dimensional hill, and figure 3-10b shows escarpment. In the case of an escarpment with sharp angles, the data at the top of figure 3-11 should be used.

For separation, distinction must first be made between configurations with mild slopes where $h/L \leq 0.5$ and configurations with steep slopes where $h/L > 0.5$. Most of the estimates are for mild slopes. Slightly larger (up to 20% at most) maximum speed-up values can occur in configurations with steep slopes, due to flow separations (See Figure 3-9b).

3.5.1 Speed Up Above the Crest of Topographical Configurations

Simple guidelines for estimating the speed-up variations near small scale topographical features for atmospheric boundary layer flow over hills with low slope are given below.

The maximum of $\triangle$ S (not of u) occurs near the surface at the hilltop. Based on this model the following guidelines are provided;

a.	$\triangle S_{max} = 2\ (h/L)$	For 2-D ridges or valley with negative value of h. Separation for valley flow can occur for slopes greater than 0.3 or less.
b.	$\triangle S_{max} = 0.8\ (h/L)$	For 2-D escarpments.
c.	$\triangle S_{max} = 1.6\ (h/L)$	For 3-D axisymmetric hills.

These estimates should only be used for h/L up to about 0.5. In separated flows, a small increase in $\triangle S_{max}$ is expected up to $\triangle S_{max} = 1.2$.

The above 2-D cases are for flows perpendicular to the 2-D configuration. For flows at an angle to the 2-D configuration, L should be adjusted as follows:

$L = L_o / \cos \theta$ Where θ id the angle between the flow direction and normal direction, L_o.

It should be noted that there may be a significant (approx. 20°) change in wind direction over 2-D terrain features for non-normal flows.

The fractional speed-up at higher elevation above the hilltop can be estimated using the exponential decay law;

$$\triangle S(o,z) = (\triangle S_{max})\ (\exp\ [-E\ z/L])$$

Where	E = 3	for 2-D hills
	E = 2.5	for 2-D escarpments
	E = 4	for 3-D hills

For an estimate of the speed-up at x not equal to zero, estimates of the decay of the speed-up away from the crest are much less certain. For hills, above the elevation of the top of the hill, the following may be used;

$$\triangle S = (\triangle S_{max}) \left(\exp\left[-E(z_1^2 + x^2)^{1/2}/L\right]\right)$$

where E = 3 for 2-D ridges
E = 4 for 3-D hills
z_1 is the height above the hill crest, see Figure 3-12

According to this equation, the constant $\triangle$ S lines become circles. This procedure gives values which are close estimates for $\triangle$ S downstream of hills. It gives slightly larger values of $\triangle$ S upstream of the hill. For estimating the velocity upstream of hills, figure 3-11 can be used.

3.5.2 Computing Optimal Anemometer Height Downwind of 2-D Slopes (Ridges and Lee Slopes)

Data obtained from wind-tunnel simulation of 40 2-D ridge and 48 2-D lee slope model simulations are summarized in Table 3-3 to show the decrease in anemometer error with distance from the hilltop and height of the anemometer above ground. A 2-D ridge has a shape approximated by Figure 3-9a while a 2-D lee slope is a hill with a broad top so that the geometry would appear as in Figure 3-10b with velocity from the right in the figure. Data are provided for open country and suburban surface roughness and for a variety of slope angles. Distance x has its origin at the point where the downward slope of the ridge or lee slope begins. The range of validity of the data in table 3-3 is for ridge or lee slope heights of 40 feet to 170 feet. Smaller ridge heights are expected to give smaller anemometer heights than listed, but possibly longer relative distances. In all cases, the anemometer should be no less than 1.5H (1.5 times the height of local roughness elements). Where an error category only appeared below 1.5H, the minimum anemometer height Z_m was set to 1.5H in Table 3-3 and X_m was set to not applicable, NA, indicating any location on the slope above elevation 1.5H is acceptable.

Example: Given: A generally flat plane breaks into a 9 degree average slope to a river bottom 80 feet below the plane. The estimated surface roughness length Z_0 is 0.03 meters (grassy area with some trees and buildings). A proposed anemometer location is 500 ft down the slope from the break. Find minimum anemometer heights to limit anemometer shielding to 20 or 30 percent.

Solution: Use table 3-3, lee slope, open country, 9 degree angle.

For 20% error distance $X_m = 9h = 9(80) = 720$ ft
For 30% error distance $X_m = 8h = 8(80) = 640$ ft

Since $X(=500) < X_m(=720 \text{ or } 640)$, the anemometer is affected by the slope.

From Table 3-3, the height requirement for;
20% error is $Z_m = 70$ ft;
30% error is $Z_m = 40$ ft.

3.5.3 Computing Optimal Anemometer Height Downwind of 3-D Slopes (Hills)

3-D hill model simulations are summarized in table 3-4 to show the decrease in anemometer error with distance from the hilltop and height of the anemometer above ground. The 3-D hill shape is approximated by figure 3-10a; however, the upwind and lee slopes need not be similar. Data are represented in a format similar to the 2-D ridge case. Downwind slope angles are limited to 9 or 10 degrees - for larger slope angles separated flow phenomena may occur and might better be predicted by a 3-D obstacle. For the 3-D hill case, the largest effects occur beyond 4 hill heights and so the anemometer height restrictions are different farther from the hilltop. Hill heights used to obtain table 3-4 were 75 ft and 150 ft high. The range of validity may reasonably be over hill heights of 40 ft to 170 ft. Smaller hill heights are expected to give smaller anemometer height requirements than those listed by a small amount.

Example: Given: A 60 ft high grassy hill with scattered 12 ft bushes (Z_o = 0.03m) has an average slope of 6 degrees. An anemometer is to be located 600 ft from the top of the downward slope. Find minimum anemometer heights to limit shielding to 20 or 30 percent.

Solution: Use table 3-4, open country, 6 degree angle, and x/h > 4.

For 20% error distance X_m = 17h = 17(60) = 1020 ft
For 30% error distance X_m = not applicable

Since X(=600) < X_m(=1020), the anemometer is influenced by the slope for 20% errors.

From table 3-4, the height requirement for;
20% error is Z_m = 50 ft;
30% error is larger of 1.5 (12) = 18 ft or 20 ft, use 20 ft to avoid 30 % error.

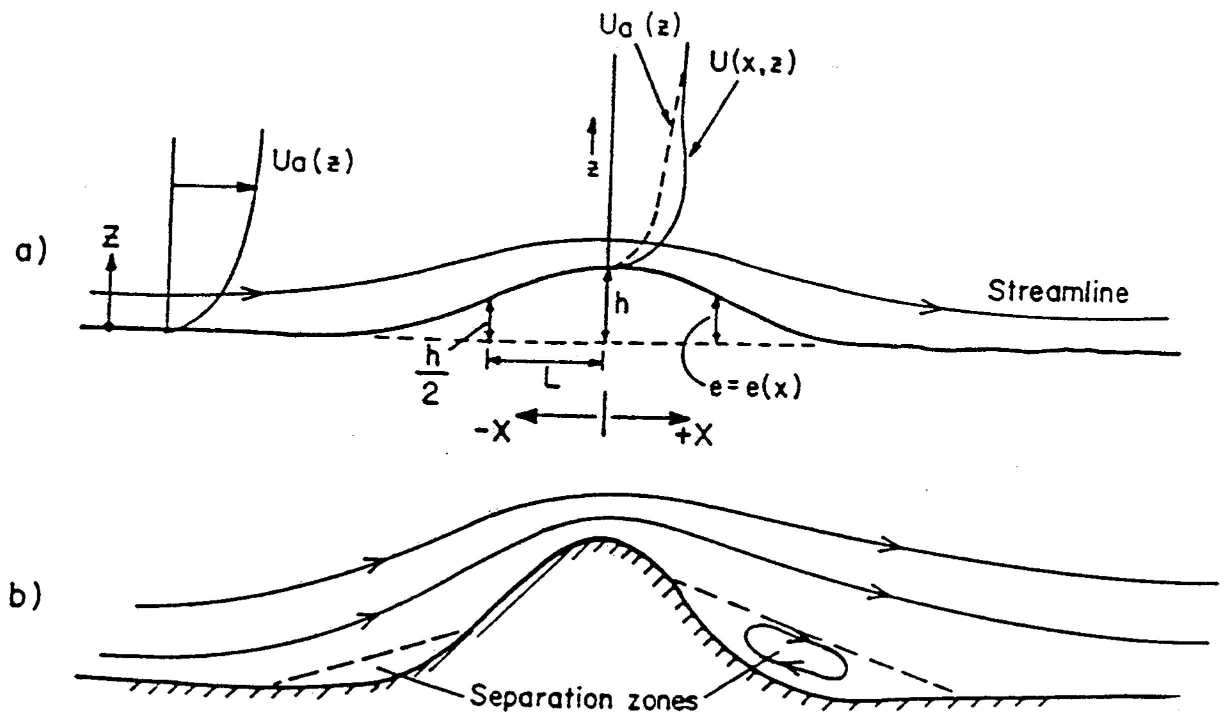


FIGURE 3-9. VELOCITY PROFILES AND SEPARATION ZONES

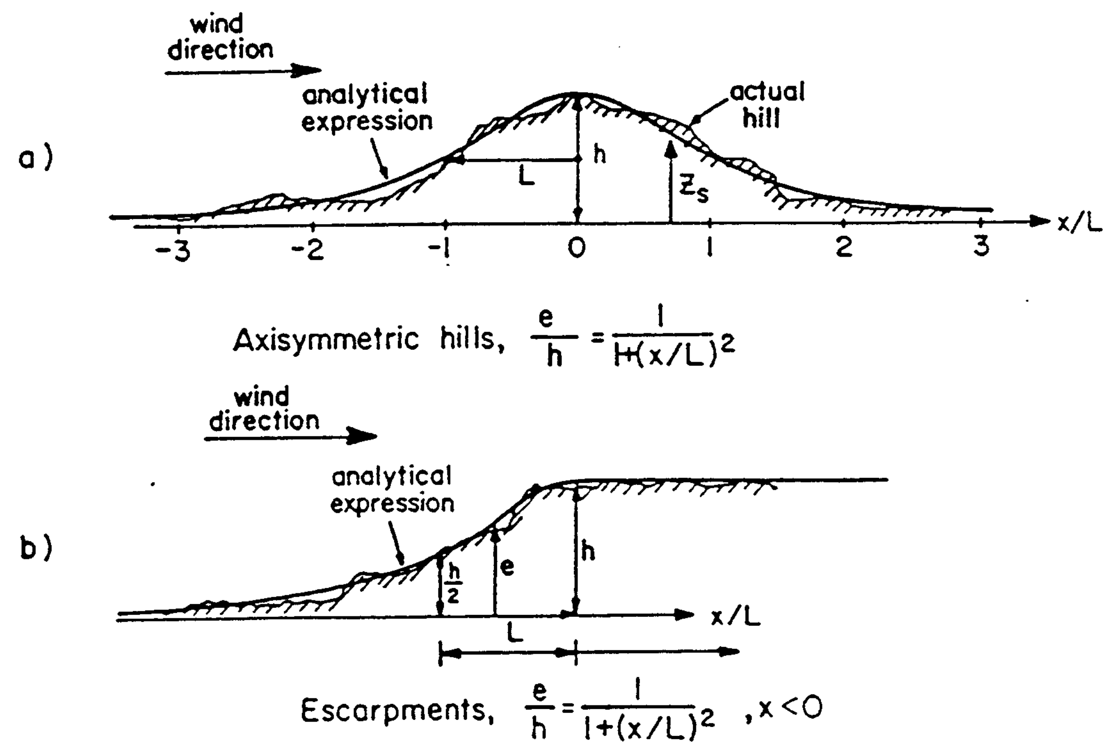
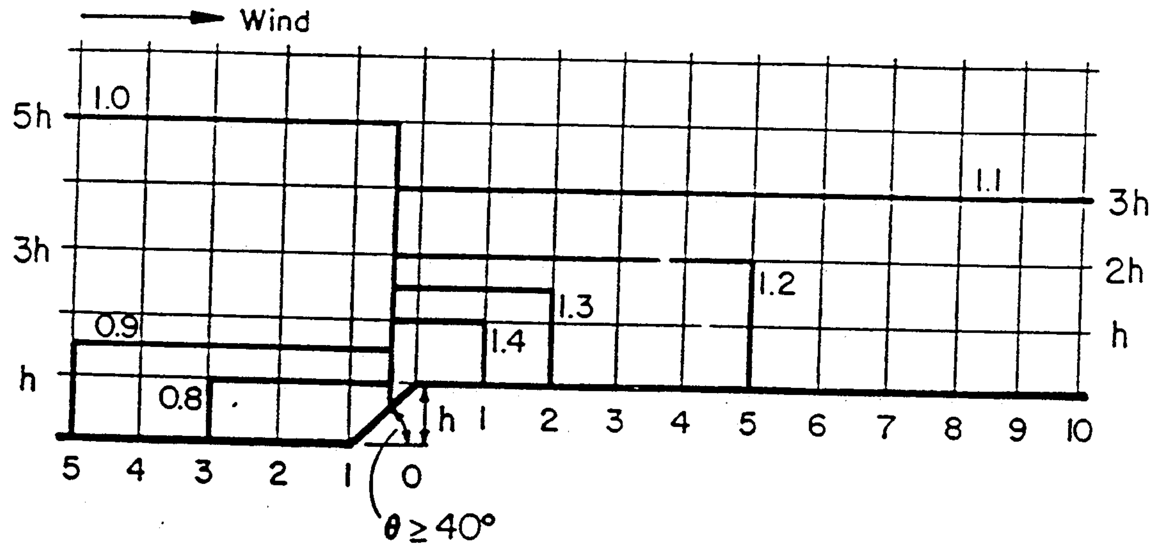


FIGURE 3-10. COMMONLY USED CONFIGURATION IN ESTIMATING THE SPEED-UP



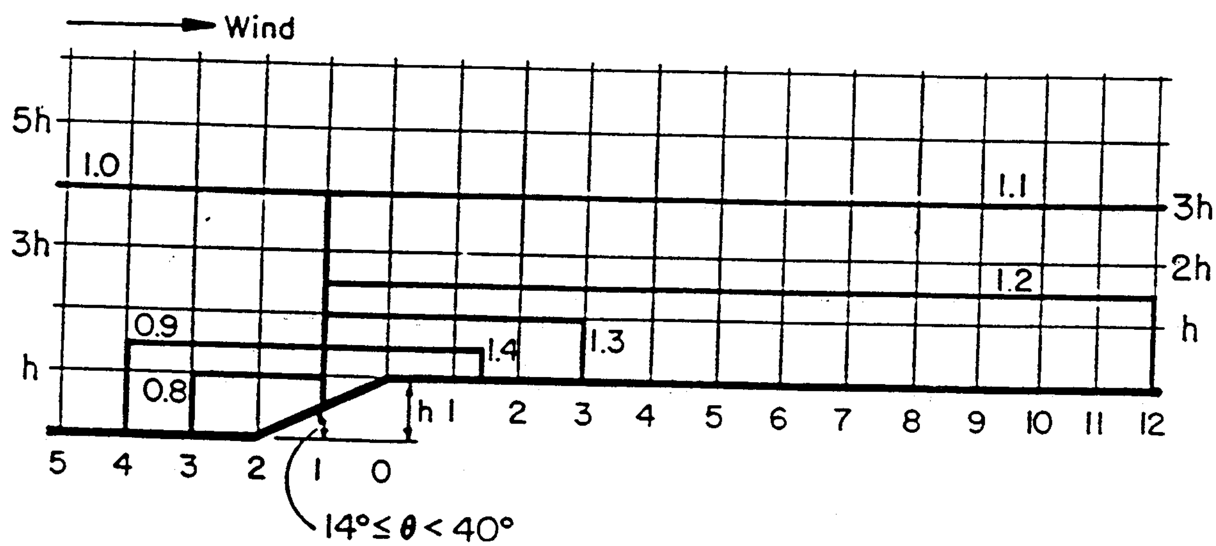


FIGURE 3-11. SIMPLIFIED CONTOURS OF AMPLIFICATION FACTOR A OVER VARIOUS ESCARPMENT SHAPES

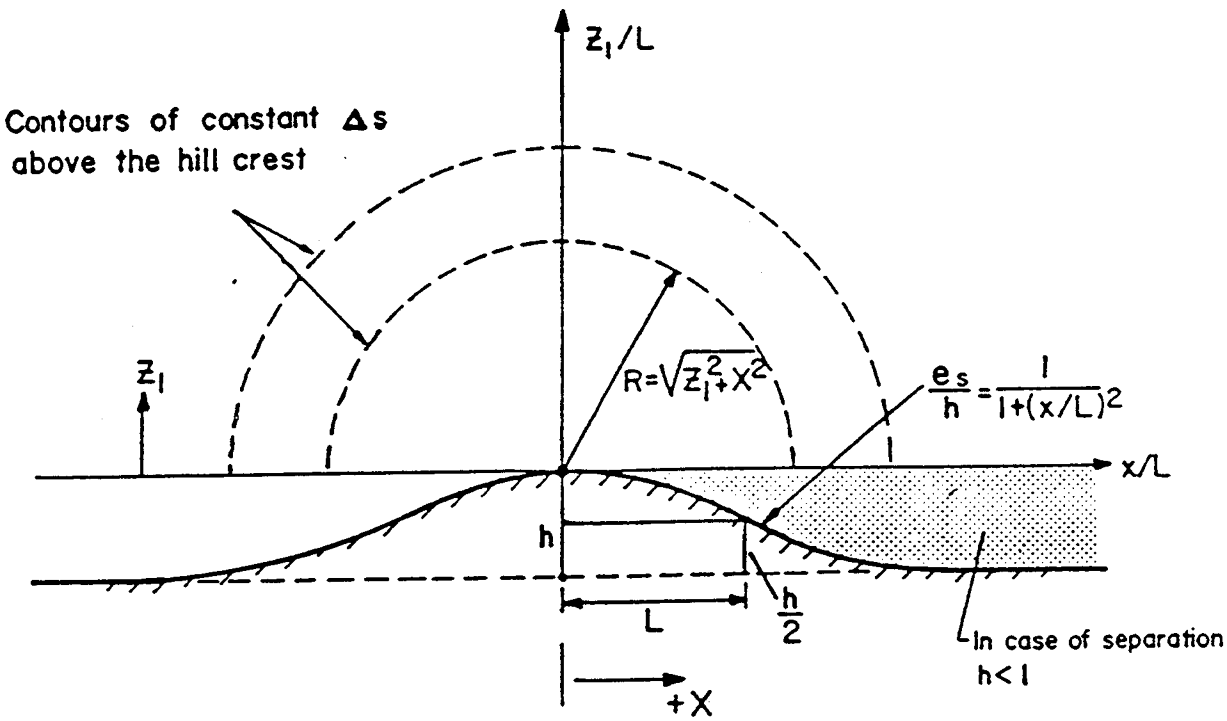


FIGURE 3-12. SPEED-UP FACTORS FOR HILLS

TABLE 3-3. HEIGHT AND DISTANCE REQUIREMENTS TO LIMIT ANEMOMETER ERRORS DOWNWIND OF 2-D RIDGES AND 2-D LEE SLOPES

2-D RIDGE (h = 40 -170 ft)

Roughness Category	X_m or Z_m, ft (see Notes)	Anemometer Error	Downwind Slope Angle, degrees 1-3	6	9	15
open country ($Z_o \leq 0.03$m)	X_m	10%	19h[1]	14h[1]	14h[1]	17h[1]
		20%	11h[2]	12h[2]	10h[2]	10h[2]
		30%	NA	NA	9h[3]	9h[3]
	Z_m	10%	45	50	75	125
		20%	20	25	45	100
		30%	1.5H	1.5H	25	90
Suburban ($Z_o \geq 0.1$m)	X_m	10%	30h	20h	17h	17h
		20%	20h	15h	12h	12h
		30%	NA	12h	11h	11h
	Z_m	10%	70	120	140	170
		20%	40	60	90	120
		30%	1.5H	50	60	110

[1]value not to exceed 1500 ft
[2]value not to exceed 1100 ft
[3]value not to exceed 900 ft

2-D LEE SLOPE (h = 40-170 ft)

Roughness Category	X_m or Z_m, ft (see Notes)	Anemometer Error	Downwind Slope Angle, degrees 1-3	5-7	9-11	15
open country ($Z_o \leq 0.03$m)	X_m	10%	NA	12h	12h	11h
		20%	NA	NA	9h	9h
		30%	NA	NA	8h	8h
	Z_m	10%	1.5H	70	120	180
		20%	1.5H	1.5H	70	70
		30%	1.5H	1.5H	40	50
Suburban ($Z_o \geq 0.1$m)	X_m	10%	24h	19	19	19
		20%	NA	12	12	12
		30%	NA	10	10	10
	Z_m	10%	70	210	220	230
		20%	1.5H	110	150	170
		30%	1.5H	100	100	140

Notes:

a. h is ridge height, H is roughness element height

b. X_m = minimum distance from top of downward slope to avoid stated error for anemometer $Z<Z_m$

c. Z_m = minimum height above ground to avoid stated error for anemometer at $X<X_m$. All Z_m must be > 1.5H

d. 1.5H indicates height Z_m of 1.5 times actual height of local roughness elements

TABLE 3-4. HEIGHT AND DISTANCE REQUIREMENTS TO LIMIT ANEMOMETER ERRORS DOWNWIND OF 3-D HILLS

$x/h>4$

Roughness Category	X_m or Z_m, ft (see notes)	Anemometer Error	Downwind Slope Angle, degrees 3	6	9
Open Country ($Z_o \leq 0.03$)	X_m	10%	30h	20h	18h
		20%	23h	17h	12h
		30%	NA	NA	NA
	Z_m	10%	70	70	70
		20%	30	50	60
		30%	1.5H	1.5H	1.5H
Suburban ($Z_o \geq 0.1$m)	X_m	10%	25h	21h	15h
		20%	22h	13h	11h
		30%	NA	11h	9h
	Z_m	10%	170	140	180
		20%	50	80	110
		30%	1.5H	50	60

$x/h<4$

Roughness Category	X_m or Z_m, ft (see notes)	Anemometer Error	Downwind Slope Angle, degrees 3	6	9
Open Country ($Z_o \leq 0.03$m)	Z_m	10%	1.5H	1.5H	1.5H
		20%	1.5H	1.5H	1.5H
		30%	1.5H	1.5H	1.5H
Suburban ($Z_o \geq 0.1$m)	Z_m	10%	1.5H	60	50
		20%	1.5H	40	40
		30%	1.5H	30	30

Notes:

a. h is hill height, H is roughness element height

b. X_m = minimum distance from top of downward slope to avoid stated error for anemometer $Z>Z_m$.

c. Z_m = minimum height above ground to avoid stated error for anemometer at $X<X_m$. All Z_m must be >1.5H or 20 ft, whichever is larger.

d. 1.5H indicates height Z_m of 1.5 times actual height of local roughness elements.

4. <u>Worked Examples</u>

The following examples provide worked examples of typical problems encountered in the siting of individual LLWAS anemometers.

4.1 <u>Example 1</u>

This example treats 3-D obstacles in a suburban environment.

4.2 <u>Example 2</u>

This example covers both a three dimensional obstacle and a forest or canopy of trees.

4.3 <u>Example 3</u>

This example combines 2-D and 3-D situations with a forest canopy.

4.4 <u>Example 4</u>

This example compares two sites, one being the least sheltered reference site, and both being impacted by a suburban to open country roughness change.

4.5 <u>Example 5</u>

This example demonstrates the combined effects of speed-up over a hill and sheltering from a canopy of trees.

4.6 <u>Example 6</u>

This example demonstrates the combined effects of an upwind 2-D ridge, trees, and a building.

LLWAS SITE EVALUATION REPORT

AIRPORT________________ STATION EXAMPLE 1 DATE____________

OBSERVATION	BEARING	DISTANCE	INCLINE	HEIGHT	WIDTH	REMARKS
1) Cluster of trees	055-065	450	6.0	52	120	
2) Cluster of trees	070-120	425	7.0	57	350	
3) Cluster of trees	120-140	700	4.75	63	200	
4) Cluster of trees	330-005	750	3.5	51	400	

LLWAS SITE EVALUATION REPORT
EXAMPLE 1

AIRPORT____________________________ DATE___________

STATION____

EVALUATOR(S) COMMENTS: This site is sitting in an open country environment, with suburbs containing clusters of trees to the NNW - SE. According to Fig. 3-1, cluster (1) causes 30% shielding, cluster (2) causes over 50% shielding, cluster (3) causes 26% shielding, and cluster (4) causes 40% shielding at the site. In order to reduce the shielding to 20% from all the aforementioned clusters, the anemometer needs to be raised to twice the height of the tallest cluster (Fig 4), which is 2 X 63' or 126'. Therefore, the anemometer should be put on a 130' pole.

PHOTOGRAPH IDENTIFICATION__________________________________

NOTE: Refer to figure numbers in practical examples for guidance.

LLWAS SITE EVALUATION REPORT

AIRPORT________________ STATION EXAMPLE 2________________ DATE________________

OBSERVATION	BEARING	DISTANCE	INCLINE	HEIGHT	WIDTH	REMARKS
Cluster of trees	037-052	130	26.5	55	150	
Cluster of trees	115-155	200	14	55	250	
Canopy of trees	195-340	50		50 (mean ht.)		α = .26

LLWAS SITE EVALUATION REPORT
EXAMPLE 2

AIRPORT____________________ DATE__________

STATION This site is sitting in a suburban environment.

EVALUATOR(S) COMMENTS: The clusters to the NE and SE are 3-D obstructions. They are only 2-4 tree heights away from the site, and therefore cause greater than 40% shielding since X_R is less than 1 (Fig. 3-3). In order to reduce the shielding to 20%, the anemometer must be at twice the tree height (Fig. 3-4) which in this case is 2 X 55' or 110'.

The adjacent canopy of trees to the west of the site has a mixture of trees ranging from 35' to 65', and therefore is somewhat rough (α= 0.26). According to Fig. 3-6, with this power law exponent, the anemometer should be 59' higher than the mean forest height in order to minimize to shielding to 20%. This puts the anemometer at 50' + 59' or 109'.

In this case, it would be best to add ten feet (to allow for tree growth), and put the anemometer on a 120' pole.

PHOTOGRAPH IDENTIFICATION____________________

NOTE: Refer to figure numbers in practical examples for guidance.

LLWAS SITE EVALUATION REPORT

AIRPORT__________ STATION EXAMPLE 3 DATE__________

OBSERVATION	BEARING	DISTANCE	INCLINE	HEIGHT	WIDTH	REMARKS
1) Tree	355-020	70	36.5	50	30	
2) Canopy of trees	100-127	900	2.0	40	Depth =600',	= .26
3) Row of trees	128-145	935	3.3	59		
4) Cluster of trees	178-192	880	3.0	50	300	
5) Cluster of trees	225-255	540	5.5	57	200	
6) Warehouse	290-305	950	2.25	42	250	

LLWAS SITE EVALUATION REPORT
EXAMPLE 3

AIRPORT______________________ DATE__________

STATION This site is sitting in a suburban environment.

EVALUATOR(S) COMMENTS: The tree (1), clusters of trees (4), cluster of trees (5) and warehouse (6) are all 3-D obstructions since their widths are less than ten times height. According to Fig. 3-2, tree (1) causes over 50% shielding, cluster (5) causes 50 % shielding, and warehouse (6) causes 21% shielding at the site. To minimize the shielding from cluster (5) to 20 %, the anemometer needs to be twice the cluster's height (Fig. 3-4), which is 2 X 57' or 114'.

The canopy (2) causes about 13% shielding at the site (Table 3-1 and Figure 3-7). The row of trees (3) is a 2-D obstruction, and therefore causes 32% shielding at the site (Fig. 3-5). In order to reduce the shielding to 20%, the anemometer should be raised to 1.7 times the height of the row of trees (Fig. 3-5), which is 1.7 X 59' or 100'.

The cluster (5) creates the requirement for the highest anemometer level (114'). Therefore, the anemometer should be placed on a 120' pole.

PHOTOGRAPH IDENTIFICATION______________________

NOTE: Refer to figure numbers in practical examples for guidance.

LLWAS SITE EVALUATION REPORT

EXAMPLE 4

AIRPORT ____________ STATION Remote Site 20' Agl DATE ____________

OBSERVATION	BEARING	DISTANCE	INCLINE	HEIGHT	WIDTH	REMARKS
Suburban interface	080-140	700				α = .24
						site = .13

LLWAS SITE EVALUATION REPORT

AIRPORT ____________ STATION EXAMPLE 4 CF Site 20 Agl DATE ____________

OBSERVATION	BEARING	DISTANCE	INCLINE	HEIGHT	WIDTH	REMARKS
Suburban interface	080-140	2200				α = .24
						site = .13

LLWAS SITE EVALUATION REPORT
EXAMPLE 4

AIRPORT____________________ DATE__________

STATION____________________

EVALUATOR(S) COMMENTS: The example compares the effect of a suburban to open country roughness change at a CF (centerfiled) site and a remote (both out of the E-S). The CF site, being the more open site, is 2200' (670 m) from the roughness change (α = .24 to α = .13), while the remote site is 700' (213 m) from the roughness change. In order to determine the ratio of the windspeed at the remote site (U(Z)r) to the windspeed at the CF site (U(Z)c) from the E-SE, (both anemometers are at 20' or 6.1 m), it is necessary to first compare the windspeed at the sites with the windspeed at the sites with the windspeeds at the sites with the windspeed at a hypothetical (10 m) reference site (U_1), located in the suburban roughness upstream of the sites, by using Table 3-2 and the steps in Section 3.4.1. The ratio of the windspeed at the remote site (X = 213 m.) to the windspeed at the reference site, U_r/u_1 = 1.15. The ratio of the windspeed at the CF site (X = 670 m) to the windspeed at the reference site, U_c/U_1 = 1.22. Therefore, the ratio of the windspeed at the remote site to the windspeed at the CF site, U_r/U_c = 15/22 = .94. This indicates that the remote site is 6% shielded compared to the CF site with E - SE winds, which is tolerable.

PHOTOGRAPH IDENTIFICATION____________________

NOTE: Refer to figure numbers in practical examples for guidance.

LLWAS SITE EVALUATION REPORT

AIRPORT__________ STATION EXAMPLE 5 DATE__________

OBSERVATION	BEARING	DISTANCE	INCLINE	HEIGHT	WIDTH	REMARKS
Terrain drops	All directions	500	-12	-80		
Canopy of trees	All directions	Adjacent		60		$\alpha = .27$

LLWAS SITE EVALUATION REPORT
EXAMPLE 5

AIRPORT______________________ DATE__________

STATION______________________

EVALUATOR(S) COMMENTS: This site is located on top of an approximately symmetric hill, and is in the middle of a rather rough canopy of trees (due to some shattering of the canopy, and the roughness of the terrain). Ignoring the speed-up factor of the hill, the anemometer would have to be 67' above the mean canopy height to reduce the shielding to 20% (Fig. 3-6). This would mandate a 60'+ 67' or 127' anemometer.

However, the hill causes a speed-up at the site. This speed-up (at the surface) is computed from the equation for ΔS max in line 3.5.1 (c), ΔS max =1.6 h/L, where ΔS max is the fractional speed-up, h is the height of the hill (80') and L is the distance from the hilltop to a point halfway down the hill (one-half of 500' or 250'). ΔS max = 1.6 (80')/(250') = 0.51. However, the anemometer will be about 100' above the surface, and therefore, the equation for ΔS above the hilltop must be used to compute the speed-up at anemometer level. This equation is: ΔS (Z) = (ΔS max)(exp[-EZ/L]), where Z is the anemometer height (100') and E is 4 for 3-D hills. ΔS(100') = (.51)(exp[-EZ/L]) = (0.51)(exp[-(4)(80')/(250')]) = 0.14; i.e., there is a 14% speed-up at 100'. Since the anemometer can tolerate 20% shielding, the combined effect of the shielding from the tree canopy and the speed-up from the hill should equal 20% shielding. Since the hill creates a speed-up factor of 14%, the tree canopy can cause no more shielding than 1-0.8/1.14 or 30%. Using Fig. 3-6, the anemometer can be 42' above the mean canopy height (60') to receive 30% shielding, or 120'. Therefore, a 110' pole should be utilized at this site.

PHOTOGRAPH IDENTIFICATION______________________

NOTE: Refer to figure numbers in practical examples for guidance.

LLWAS SITE EVALUATION REPORT

AIRPORT________ STATION EXAMPLE 6 DATE________

OBSERVATION	BEARING	DISTANCE	INCLINE	HEIGHT	WIDTH	REMARKS
1a) Ridge (base)	010-120	500	0	0		
1b) Ridge (top)	010-120	1100	7.6	150		
2) Tree	150-160	300	8.5	50	52	
3) Building	240-270	800	2.0	33	415	
4) Cluster of Trees	290-310	500	6.3	60	175	

LLWAS SITE EVALUATION REPORT
EXAMPLE 6

AIRPORT________________________ DATE__________

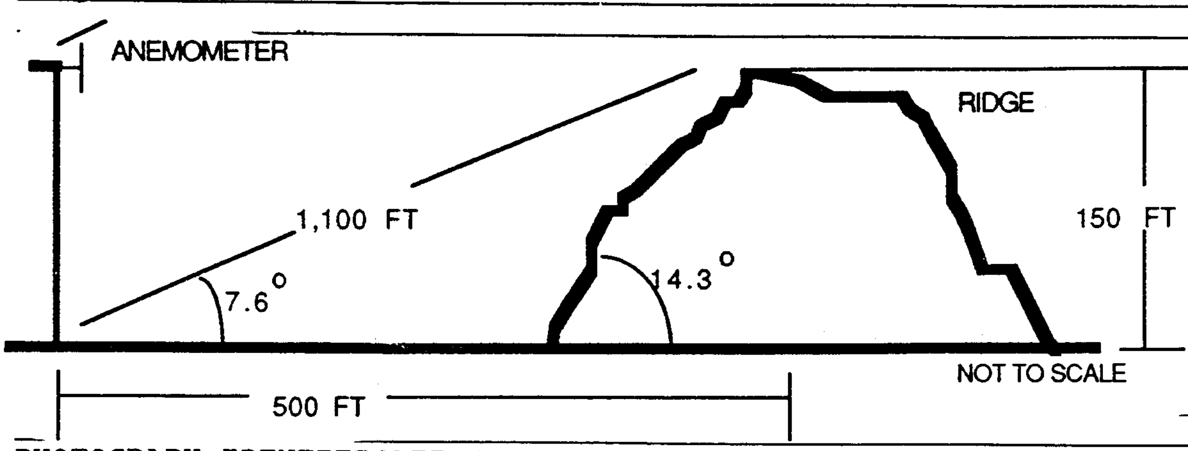
STATION____

EVALUATOR(S) COMMENTS: The drawing below shows the positions of the ridge and anemometer. The station is in an open country environment. Using Table 3-3, 2-D ridge, open country, 15° angle; 20% error distance X_m = 10h = 1,500'. Since X (=1,100) is less than X_m(=1,500), the anemometer is affected by the ridge. From Table 3-3, the height requirement for 20% error is Z_m= 100'.

The tree and cluster of trees are 3-D obstructions. From Fig. 3-1, the tree causes 23% error, and the cluster causes 33% error. In order to reduce the error to 20% from the tree and the cluster, the anemometer needs to be raised (using Fig. 3-4) to 88' to 120', respectively.

The building is 2-D obstruction. From the formula in Section 3.2.1 for low obstacles. The building causes 17% error, which is tolerable.

Therefore, the anemometer should be placed at 120' in order to counteract the effects of both the cluster of trees and the ridge.



PHOTOGRAPH IDENTIFICATION________________________

NOTE: Refer to figure numbers in practical examples for guidance.